High Fidelity IBR Generic Model Development and Validation

for Planning, Operating and Protection Studies

Background and Motivation

Jens Boemer, Deepak Ramasubramanian,
Mobolaji ("Mobs") Bello, EPRI
John Seuss, DOE SETO

2023 Fall Technical Workshop
Monday, October 23rd, 2023
San Diego, CA

Classification: Public

SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

This work is, in part, supported by the U.S. Department of Energy, Solar Energy Technologies Office under Award Number DE-EE0009019 *Adaptive Protection and Validated MODels to Enable Deployment of High Penetrations of Solar PV (PV-MOD).* https://www.epri.com/pvmod

Abstract

This tutorial presents the current state of **validated** models, the use of these **generic models** in the positive-sequence **fundamental-frequency** domain **and electromagnetic transient domain**, and seeks feedback on future improvements.

The tutorial is based on the DOE-funded **PV-MOD project**, which develops and validates high-fidelity (generic) models of solar photovoltaic, energy storage, and other inverter-based resources for use in power system analysis (https://www.epri.com/pvmod).

The tutorial will explore the use of generic **models conforming with IEEE standards 1547 and 2800** technical minimum requirements to foster understanding of those requirements and to generate reference traces that could be used in plant-level **conformity assessment during the interconnection process**.

Acknowledgements and Disclaimers

Acknowledgments

This work is supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office under Award Number DE-EE0009019 *Adaptive Protection and Validated MODels to Enable Deployment of High Penetrations of Solar PV (PV-MOD)*. https://www.epri.com/pvmod

We acknowledge the valuable contributions to this tutorial by Wes Baker during his tenure with EPRI, and who developed a generic photovoltaic inverter model in an electromagnetic transients simulator for transmission connected plants in his Ph.D. dissertation that created the foundation for the model presented in this tutorial:

- W. Baker, "Control, Modeling, and Analysis of Inverter-Based Resources," Ph.D. PhD Dissertation, Electrical and Computer Engineering, Auburn University, 2021. [Online]. Available: https://etd.auburn.edu//handle/10415/7978.

Moderators & Instructors

John Seuss, Ph.D.

Education

- 2016—Doctoral degree in Electrical Engineering from the Georgia Institute of Technology
- 2006—Bachelor degree in Electrical Engineering from the Georgia Institute of Technology

- Technology Manager in the Systems Integration group in the Solar Energy Technologies Office (SETO) of the U.S. Department of Energy (DOE)
  - Manages funding opportunities for research, development, demonstration, and deployment of new technologies that will aid the integration of solar energy with the electric grid
- Previously worked in the utility industry as an engineer, researcher, and product developer under various topics including
  - Renewable integration, inverter controls,
  - Distribution automation, adaptive protection systems

Moderators & Instructors

Mobolaji ("Mobs") Bello

- Technical Leader in EPRI's team for Transmission Operations and Planning
- 23+ years experience with Transmission and Distribution Operations and Planning
- Senior member of IEEE.
- Chartered Engineer (CEng)
- International Professional Engineer (Int. PE) with the Engineering Council in the United Kingdom (UK)

Education

- MScEng - Electrical Engineering
- MSc - Technology Management and Innovation
- BEng(Hons) Electrical Engineering
- BSc(Hons) degree in Industrial and Systems Engineering.

Moderators & Instructors

Jens Boemer, Ph.D.

Education

- 2016—Doctorate (Ph.D., Dr.-Ing.), Delft University of Technology, NL
  - Thesis title: *On Stability of Sustainable Power Systems: Network Fault Response of Transmission Systems with High Penetration of Distributed Generation*
- 2005–2006—Postgraduate Program in International Affairs, Robert Bosch Scholarship
- 2005—Graduate engineer (Dipl.-Ing.) in Electrical Engineering, Technical University of Dortmund, DE

- Technical Executive in EPRI's Grid Operations and Planning Group
  - Works across groups like DER Integration
- 15+ years experience with reliably integrating renewable and distributed energy sources into grids in
  - Germany, Ireland, United States, etc.
- Expertise in
  - Inverter-based resources (IBR) performance
  - Modeling of IBR plants and DER aggregates
  - Stakeholder consensus building/ standards
- Industry leadership in IEEE standards development of 1547 and 2800

Moderators & Instructors

Deepak Ramasubramanian, Ph.D.

- Senior Technical Leader in EPRI's Grid Operations and Planning Group
  - Leads the group's projects on Modeling and Analytics for Emerging Technologies
- Engages with various utilities and transmission system operators around the world mostly to study the impact of increase in inverter-based resources in their system
  - Recognized for his work on grid forming inverter modeling and control along with low short circuit strength analysis
- Expertise in
  - modeling, control and stability analysis of the bulk power system
  - impacts of large-scale integration of inverter interfaced generation and load

Education

- 2017—Ph.D. degree in Electrical Engineering from the Arizona State University, Tempe, USA
  - Thesis title: *Impact of converter interfaced generation and load on grid performance*
- 2013—M.Tech. degree in Power Systems from the Indian Institute of Technology Delhi, New Delhi, India
- Awards
  - 2022 IEEE PES Chapter Outstanding Engineer Award
  - Energy Systems Integration Group (ESIG) Excellence Award
  - North American SynchroPhasor Initiative (NASPI) Outstanding Graduate Student Award
  - Power System Operation Corporation (POSOCO) Power System Award

Content
(9:00 a.m. – 12:00 p.m.)

9:00 a.m. **Background and Motivation**
John Seuss & Jens Boemer

9:15 a.m. **High-level review of Power Electronics Basics for PV Inverters, IBR Controls, and Applicable IEEE Standards**
Jens Boemer

9:30 a.m. **Generic IBR Positive Sequence Models for Solar PV and Storage**
Deepak Ramasubramanian

10:20 a.m. **Break (time for some Q&A)**

10:40 a.m **Generic EMT Model for Solar PV and Storage conforming with IEEE 2800-2022**
Deepak Ramasubramanian

11:10 a.m. **Potential Use Cases of Generic Models to Generate Reference Traces for Plant-Level Conformity Assessment in the Interconnection Process**
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11:40 a.m. **High-level review of DER Modeling for Transmission Planning Studies**
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11:45 a.m. **Additional Q&A / Overflow**

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Undesired Solar PV Plant Performance

- **Unexpected** tripping, cessation of active power, oscillations, etc.
- **Mis-application of IEEE 1547** standard for Transmission connected resources
- **Opportunity for standardization of IBR** performance to **reduce uncertainty of** IBR unit and plant **response**

➢ **IBR models are *one* tool to understand potential reliability impacts and determine desired IBR response.**

https://www.nerc.com/pa/rrm/ea/Pages/Major-Event-Reports.aspx

MOD-026-2 – Verification of Dynamic Models and Data for BES Connected Facilities

A. Introduction

1. **Title:** Verification of Dynamic Models and Data for BES Connected Facilities
2. **Number:** MOD-026-2
3. **Purpose:** To verify that the dynamic models and associated parameters used to assess Bulk Electric System (BES) reliability represent the in-service equipment of BES Facilities including generating Facilities, transmission connected dynamic reactive resources, and high-voltage direct current (HVDC) systems.

https://www.nerc.com/pa/Stand/Pages/Project-2020_06-Verifications-of-Models-and-Data-for-Generators.aspx

https://www.nerc.com/pa/Stand/Pages/Project2022-04EMTModeling.aspx

Project 2022-04 EMT Modeling

Related Files

Status
The comment and nomination period for the **Project 2022-04 EMT Modeling Standard Authorization Request (SAR)** concluded at **8 p.m. Eastern, Tuesday, September 13, 2022.**

Background
The bulk power system (BPS) in North America is undergoing a rapid transformation towards high penetrations of inverter-based resources. Transmission Planners (TP) and Planning Coordinators (PC) are concerned about the lack of accurate modeling data and the need to perform electromagnetic transient (EMT) studies during the interconnection process and long-term planning horizon. The growth of inverter technology has pushed conventional planning tools to their limits in many ways, and TPs and PCs are now faced with the need to conduct more detailed studies using EMT models for issues related to inverter-based resource integration issues.

This SAR proposes including EMT models and studies in planning-related NERC Standards to ensure reliable operation of the BPS moving forward.

Standard(s) Affected: FAC-002, MOD-032, and TPL-001

Purpose/Industry Need
This project addresses the reliability-related need and benefit by ensuring TPs and PCs have the models and tools necessary to adequately conduct reliability assessments under increasing levels of inverter-based resources. This requires the collection of EMT models by applicable entities and TPs and PCs to conduct EMT studies where needed.

Source: NERC, 2017-2022

DOE's Solar Energy Technologies Office FY19 Funding Opportunity Announcement

- **FY19 FOA - $138M across all five Solar Office subdivisions**
- **Topic 5 – Advanced Solar Systems Integration Technologies**
  - Topic 5.1 – Adaptive Distribution Protection Systems
  - Topic 5.2 – Grid Services from BTM DER
  - Topic 5.3 – Advanced PV Controls and Cybersecurity
- **5.1 – Adaptive Distribution Protection Systems**
  - Subtopic 5.1.A – Advanced Dynamic Models for Smart Inverters
  - Subtopic 5.1.B – Adaptive Protection for Distribution Grids
- **5.1.A - Advanced Dynamic Models for Smart Inverters**
  - Successful projects should propose enhancements to one or more of:
    - Reduced-order models that do not compromise accuracy
    - Hi-fidelity models that better represent dynamics under faults or extreme events
    - New models that integrate emerging smart inverter functionalities
  - Successful projects should validate models against test cases, simulated date, or field measurements

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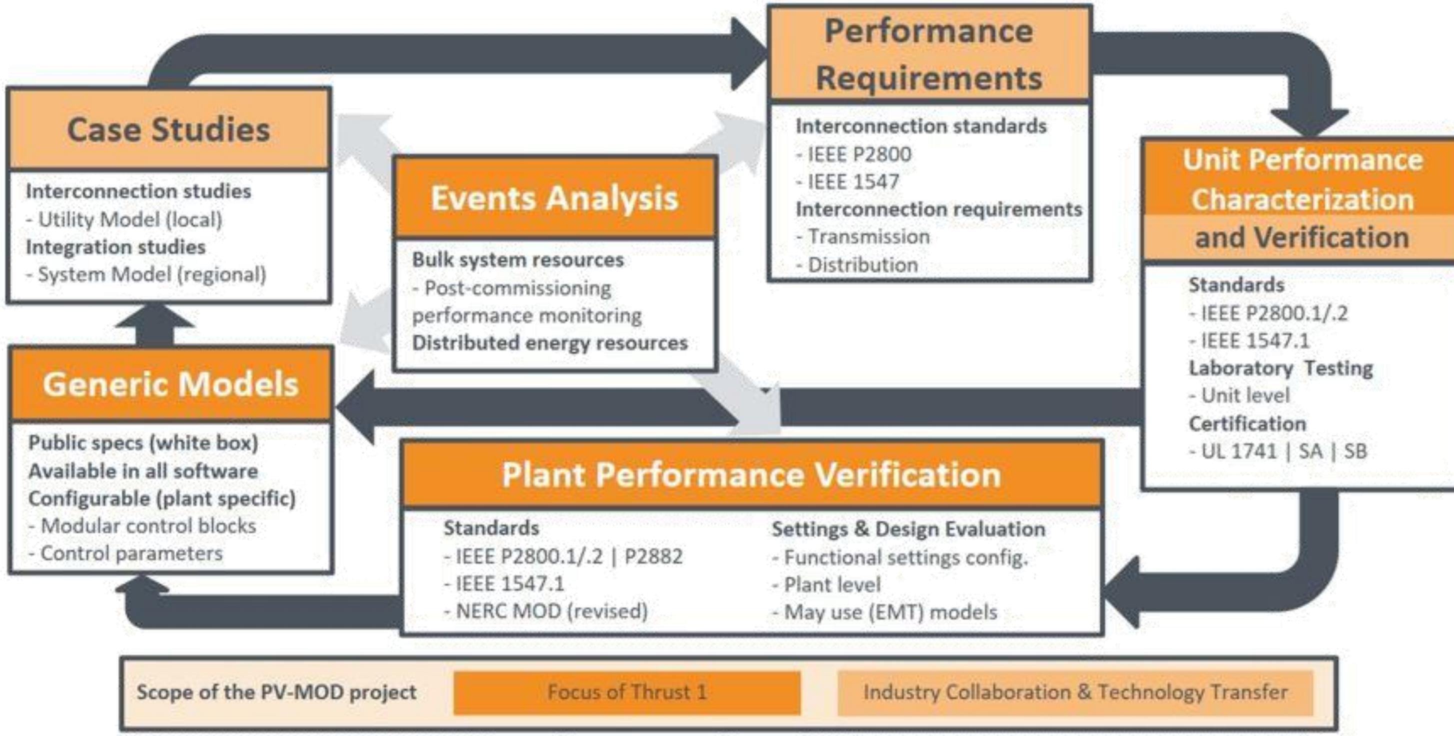
EPRI: Adaptive Protection and Validated Models to Enable Deployments of High Penetrations of Solar PV (PV-MOD)

SETO FY19 Funding Opportunity

- **Project goals (Modeling Thrust):**
  - Develop high-fidelity IBR models
  - Validate against lab tests and field measurements
  - Increase availability of generic models in commercial software
  - Transfer knowledge of using generic models to power systems engineers
- **Models and analysis include:**
  - Electromagnetic transients (EMT)
  - Power quality and harmonics
  - Short-circuit
  - Quasi-static Time Series (QSTS)
  - T&D Co-simulation

Model Development, Validation, and Commercialization Thrust



PI: Jens Boemer, EPRI

Project website: https://www.epri.com/pvmod

PV-MOD Project Overview https://www.epri.com/pvmod

Validated; publicly available models for various types of studies, reports detailing the research, close collaboration with industry stakeholders (NERC, WECC, IEEE, etc.)

Resource Characterization

- Lab Testing
- Field Data

Gap Analysis

- Existing Models

Model Specification & Implementation

Verify → Develop → Test

- Stability
- EMT
- Protection
- Power Quality
- QSTS

Transmission Planning

Model Commercialization

Software Vendors

Distribution Planning

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NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

This deliverable is, in part, supported by the North American Electric Reliability Corporation (NERC) under EPRI contract 20011165 *Inverter-Based Resources Dynamic Response Characterization for Bulk Power System Protection, Planning, and Power Quality*.

PV-MOD Project Results To Date

PV-MOD website https://www.epri.com/pvmod

First round of inverter test results

- Developed and refined draft test plan; latest update in January 2023
- Tested and analyzed results for a 36.6 kVA small-scale legacy inverter and a 8 kVA solar PV/battery storage inverter
- Tested and analyzed results for a 2.2 MVA large-scale BESS inverter with most of the latest IEEE capabilities in two configurations: one for distribution performance (per IEEE 1547-2018) and one for transmission configuration (per IEEE 2800-2022)

Collection of field measurements

- Developed field measurement guidelines
- Collected and analyzed field data for five events provided by NERC, built relationships to obtain data from IEEE, SRP, SoCo, and TVA
- Preliminary and successful validation of various model types

Generic model improvements and specifications

- Steady-state short-circuit model improvements and vendor engagement
- Hybrid power quality model specification and vendor engagement
- OpenDER, IEEE 1547-2018 compliant individual DER phasor-domain model specification with ability to extent into an EMT model
- Phasor-domain (RMS) Aggregate DER model improvements
- Generic time-domain (EMT) large-scale IBR model specification and preliminary validation

Significant and impactful industry engagement

- WECC MVS/REMWG | NERC IRPS & SPIDER | IEEE Task Forces, 2800 and P2800.2 Working Groups | IREC FIGII
- EPRI Distribution Advanced Modeling WG (DAWG), OpenDER User Group (DERMUG) | EPRI TechTransfer Webinars | EPRI Supplemental Projects related to PV-MOD

Tutorial Objectives

Objective 1

Learn about foundation, **uses cases**, and limitations of generic models for solar PV plants.

Objective 2

Update on recent generic model **improvements and validation** examples in the PV-MOD project

Objective 3

Raise awareness of **emerging role of generic EMT models** for performance specification and conformity assessment of solar PV plants

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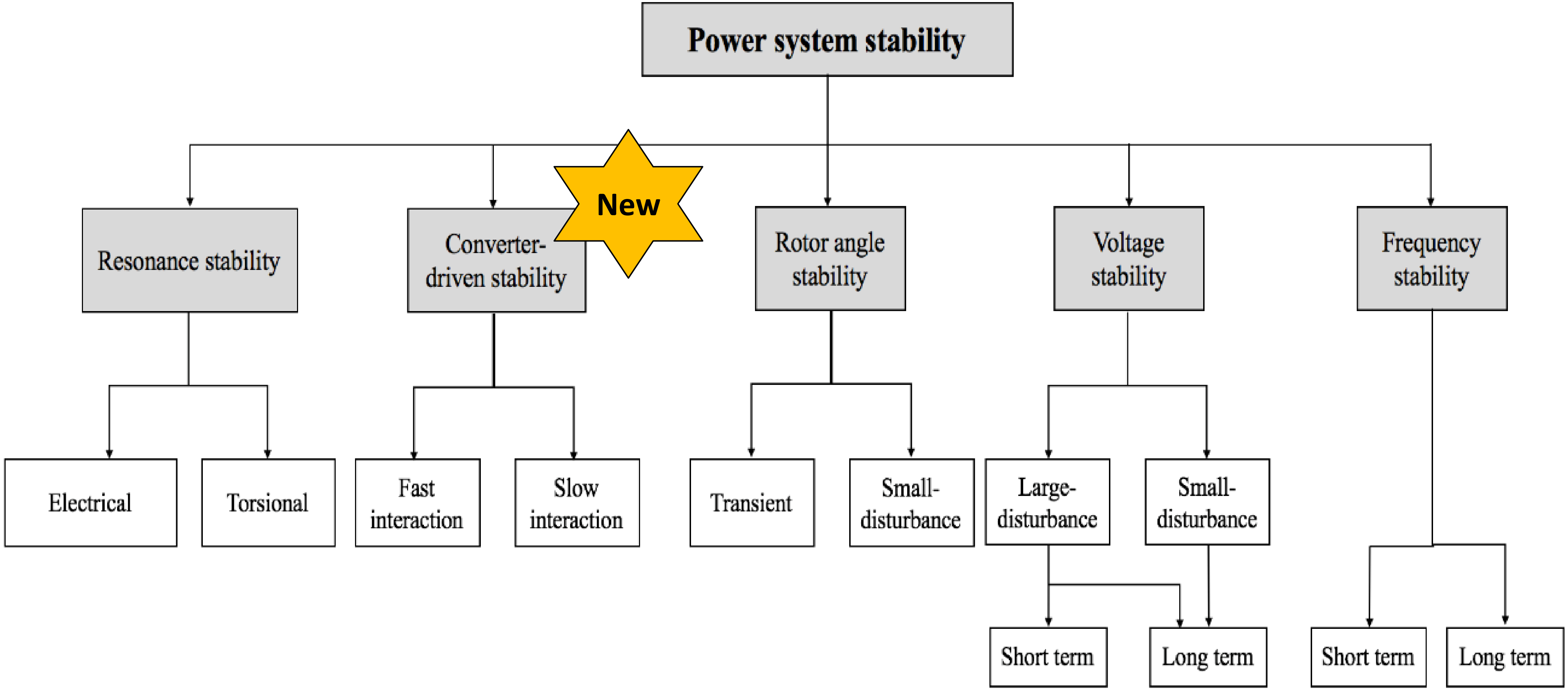
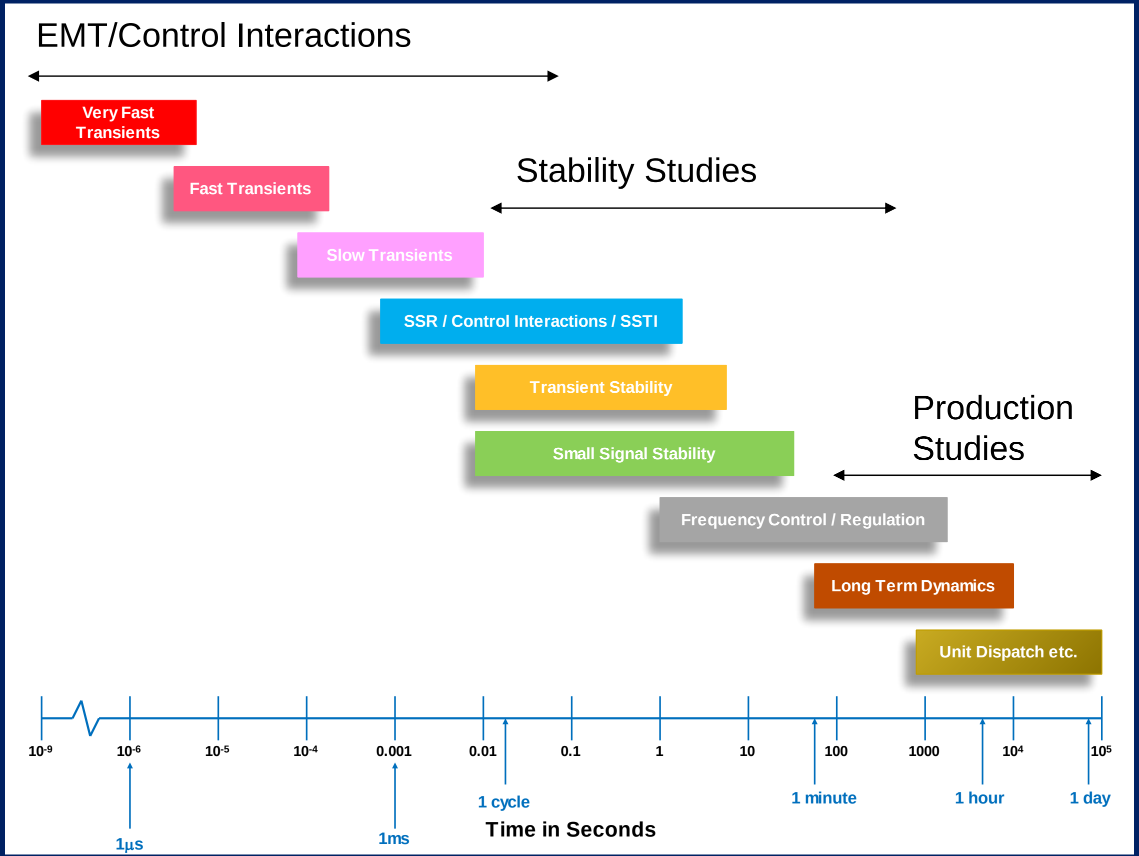
Introduction

Power System Stability Categories in Systems with Inverter-Based Resources



Source for figure above: IEEE TF Paper Definition and Classification of Power System Stability – Revisited & Extended, IEEE Transactions on Power Systems (Volume: 36, Issue: 4, July 2021), https://ieeexplore.ieee.org/document/9286772

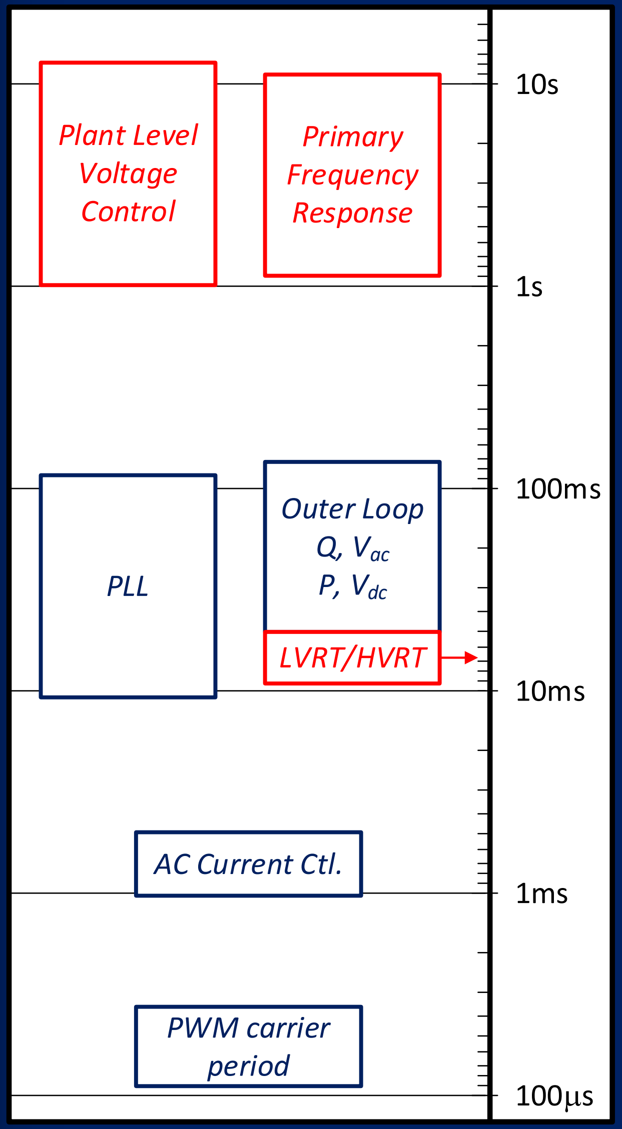
Model Type and Complexity Depend on Study Objective



Source: Power and Energy, Analysis, Consulting and Education, PLLC (2021)

- Not one model must represent all timeframes.
- What is the model used for?
  - Long-term/ futuristic planning studies
  - Interconnection/impact studies
  - Conformity assessment/ design eval.

Model Type and Complexity Depend on Study Objective



W. Baker, "Control, Modeling, and Analysis of Inverter-Based Resources," Ph.D. PhD Dissertation, Electrical and Computer Engineering, Auburn University, 2021. Available: https://etd.auburn.edu//handle/10415/7978

- Stability
- EMT
- Protection
- Power Quality
- QSTS

- Not one model must represent all timeframes.
- What is the model used for?
  - Long-term/ futuristic planning studies
  - Interconnection/impact studies
  - Conformity assessment/ design eval.
- Trade-off between model accuracy/ detail and practicability, including:
  - computational performance
  - configurability/ # parameters

➔ Industry **education** and **conversation** is an important part of model development, improvement, and application.

Focus of PV-MOD Project is on Generic Models

Generic Models

(Tend to be Moderately Accurate/Detailed)

- Developed to be agnostic of any specific vendor's equipment or control structure
- **May be limited to representation of standardized technical minimum performance**
- Available in model libraries of commercial software tools
- White-box and configurable; may not allow for 1:1 control parameter mapping

Generic parameters → Research applications - Future int. reqs.

Plant specific parameters → Specific equipment, plant design, configuration, and settings **(approximation)**

Application Examples: Interconnection Screens*, Transmission Planning Studies

* Only if interconnection performance requirements are well defined (e.g., IEEE Stds)

User-Defined Models

(Tend to be Highly Accurate/Detailed)

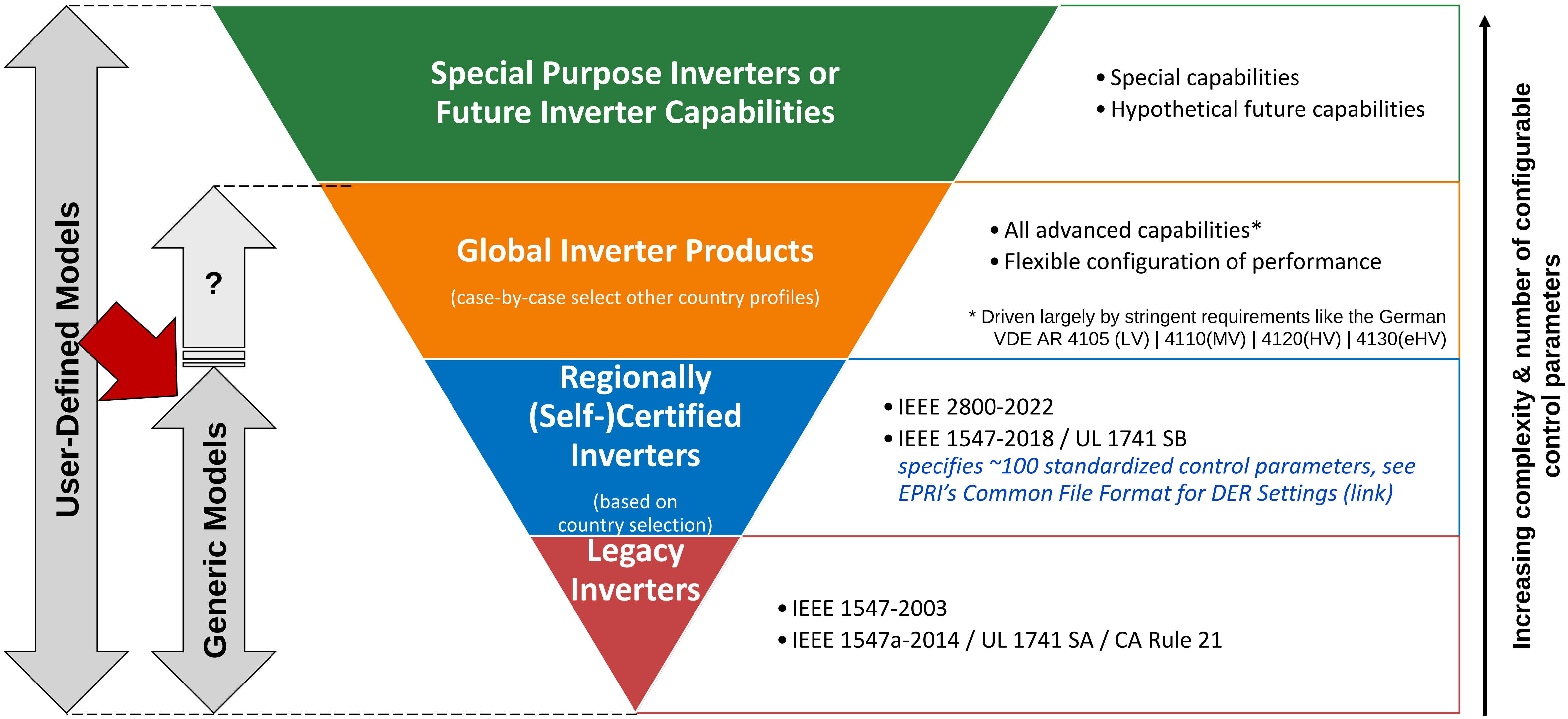
- Developed to represent specific equipment and control structures
- **May represent performance of and above standardized technical minimum**
- Not available in model libraries of commercial software tools
- Likely proprietary and "black-box" with selective configurability that may differ between OEMs; may allow for 1:1 control parameter mapping

Generic parameters → Parameterized based on:
- Default config./settings
- R&D

Plant specific parameters → Specific equipment, plant design, configuration, and settings **(more detailed)**

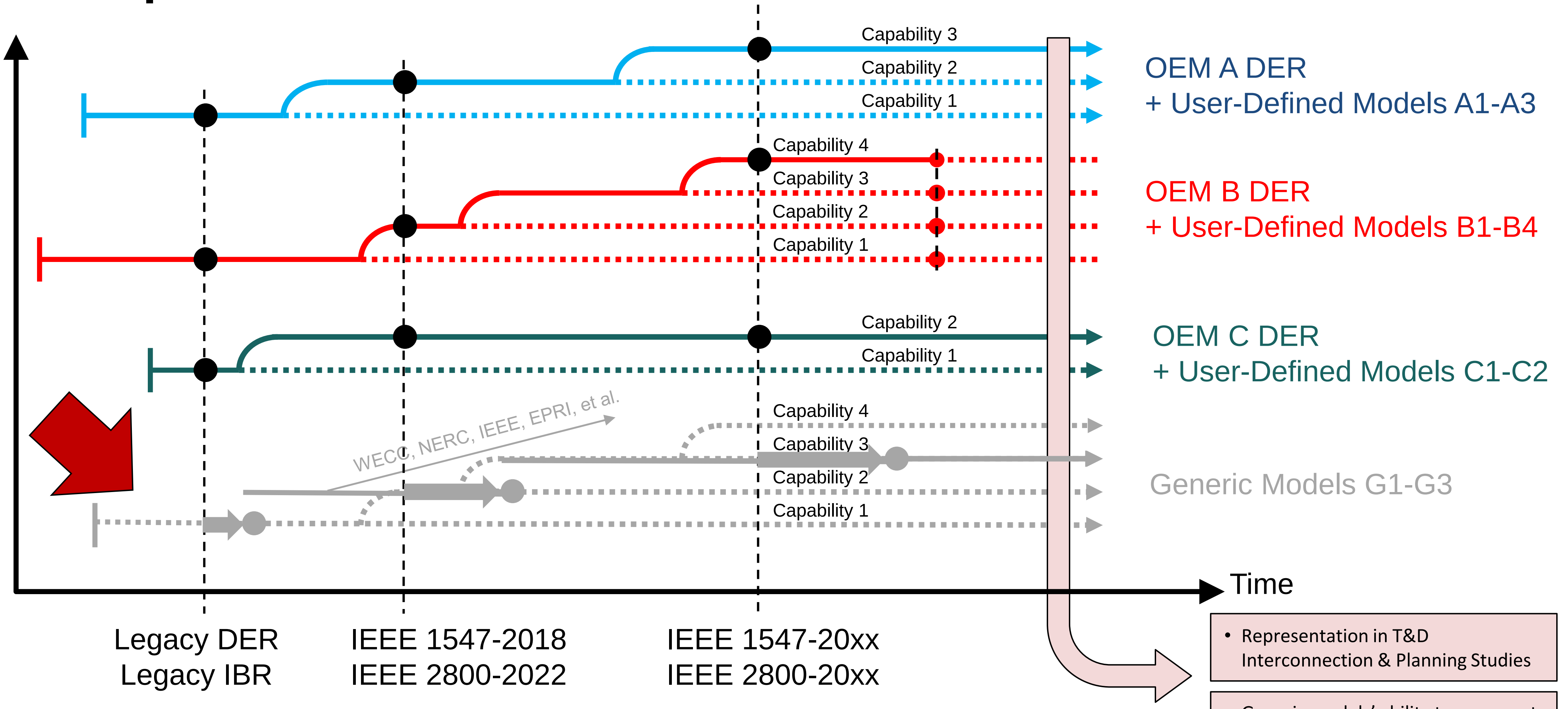
Application Examples: Interconnection / System Impact Studies

PV-MOD Generic Models Focus on North American Products



Identification of critical generic model specifications per study type and objective.

Generic Models May Always Lag Behind OEMs' Continuous Product Improvements



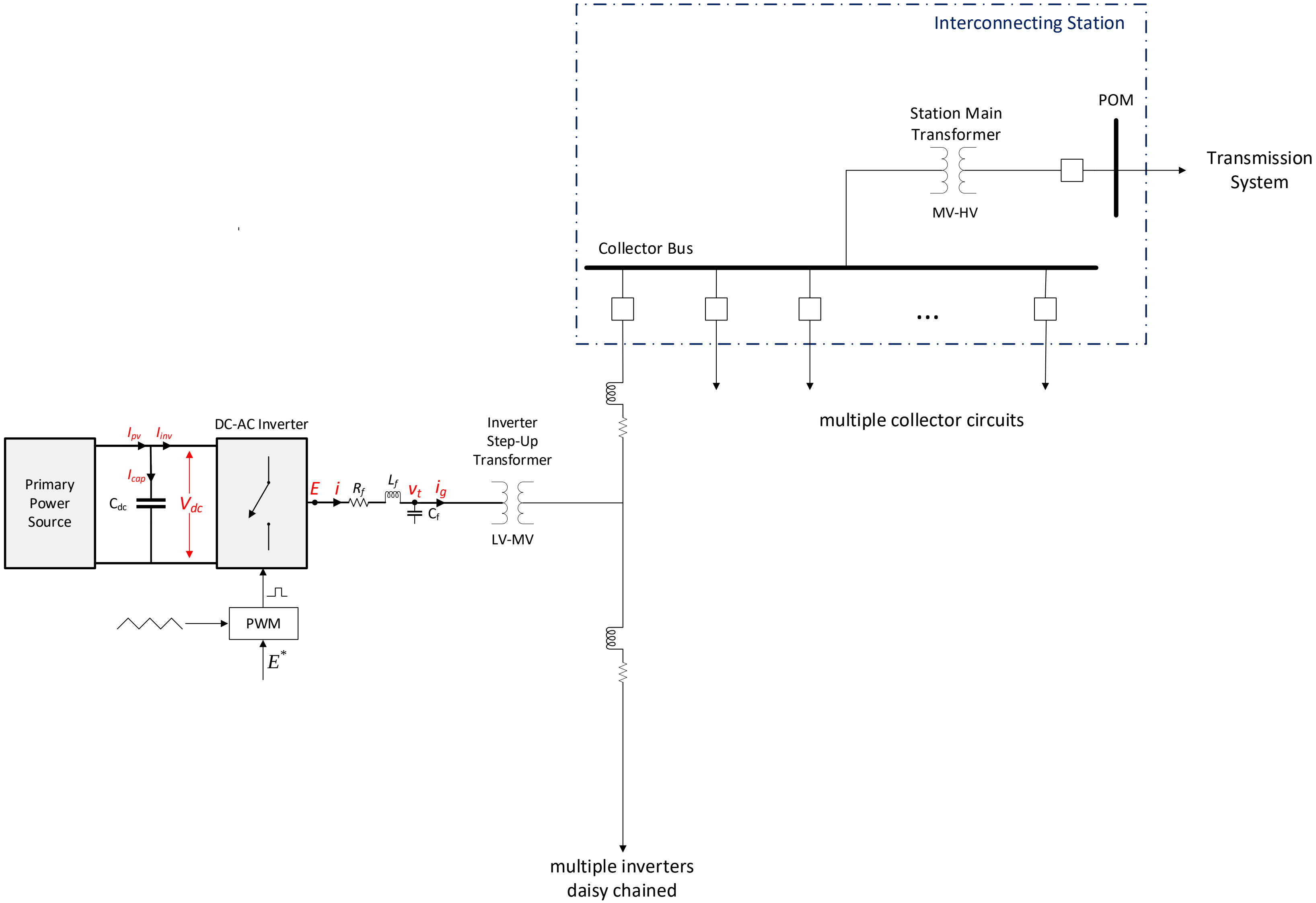
- Representation in T&D Interconnection & Planning Studies

- Generic models' ability to represent new capabilities may always lag behind user-defined models' ability.

Identification of critical generic model improvements are subject to study type and objective.

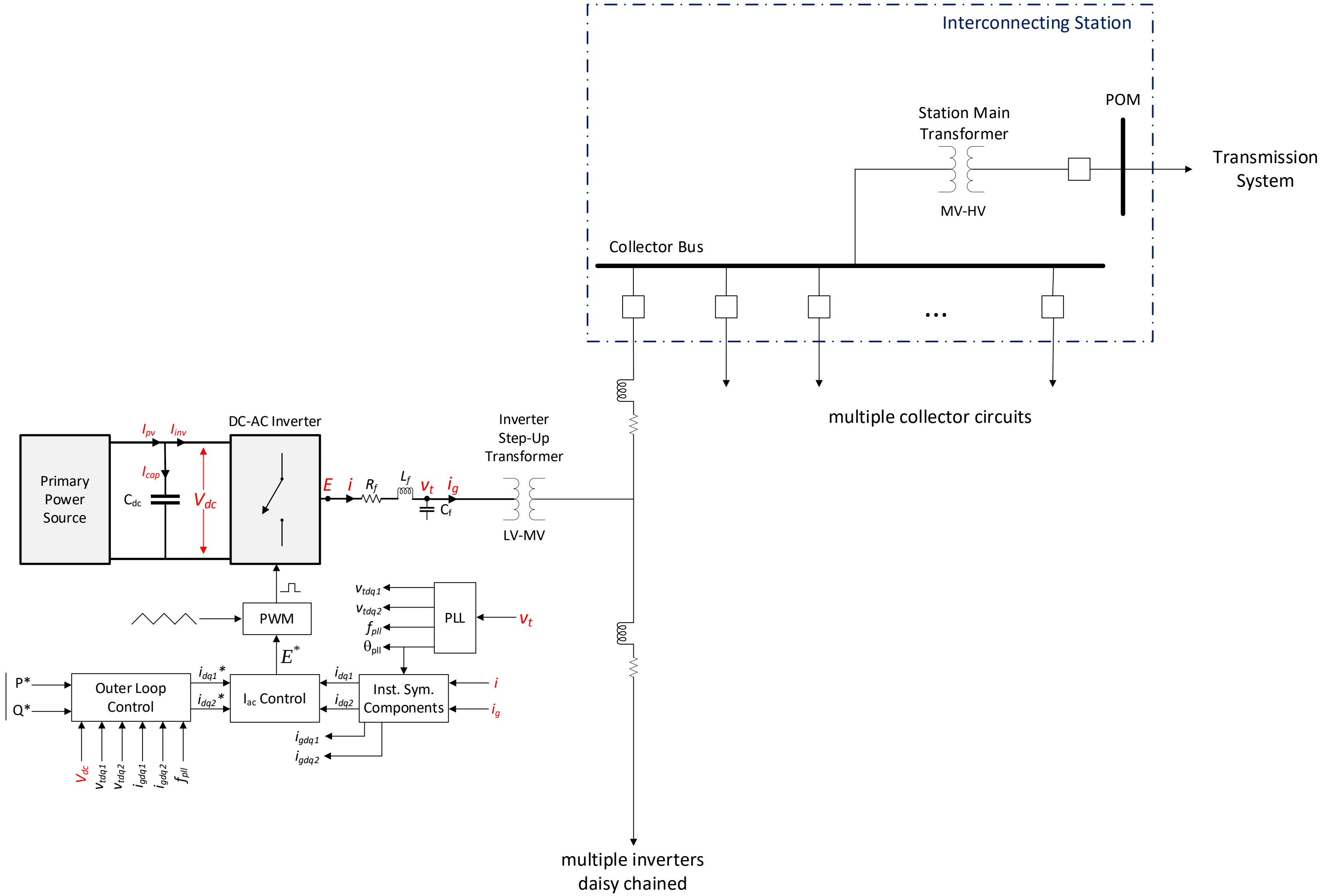
PV Plant Control Overview

Inverter

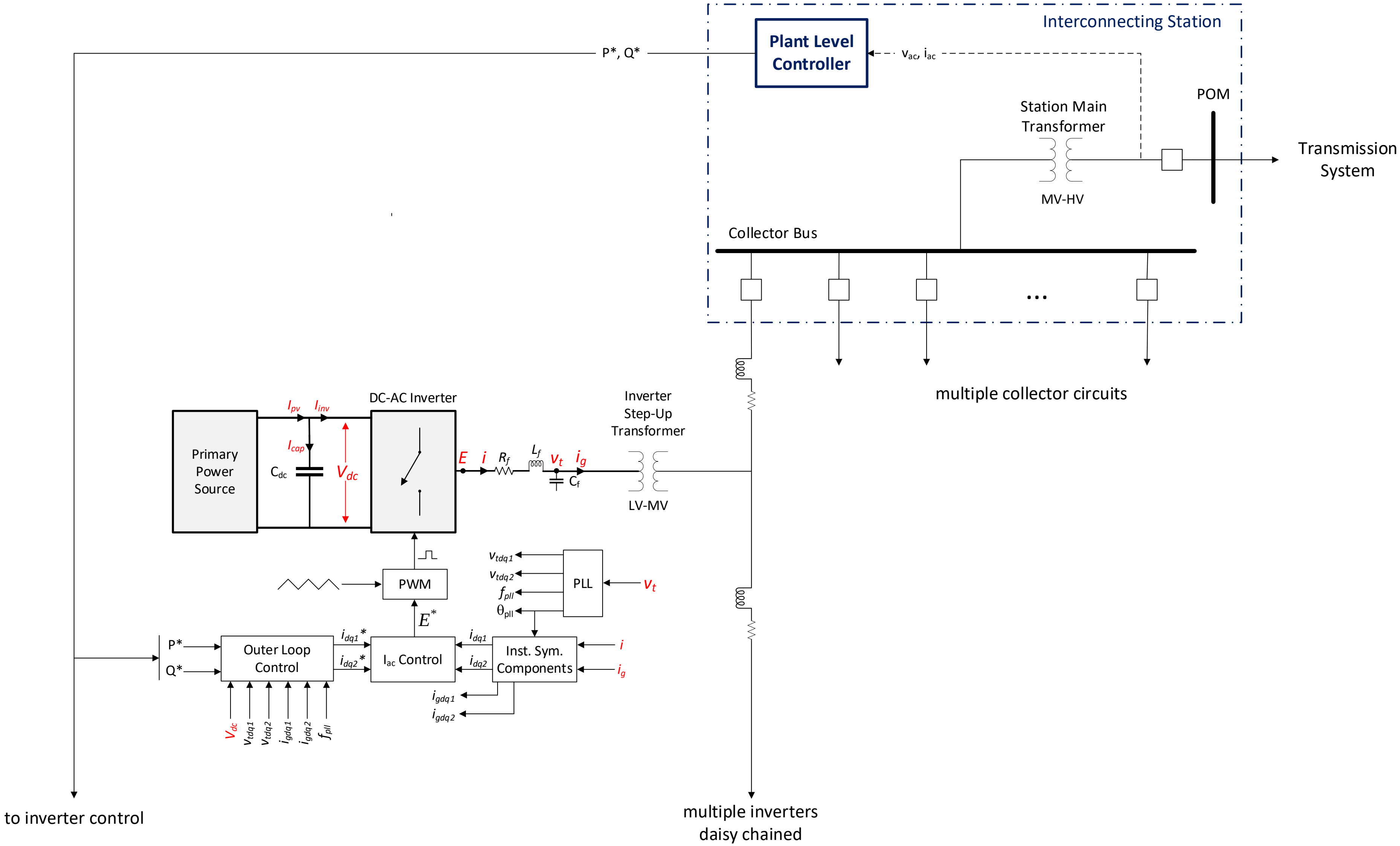


Interconnecting Station
Station Main Transformer
POM
Transmission System
MV-HV
Collector Bus
...
multiple collector circuits
DC-AC Inverter
Inverter Step-Up Transformer
Primary Power Source
I_{pv}
I_{inv}
I_{cap}
C_{dc}
V_{dc}
E
i
R_f
L_f
v_t
i_g
C_f
LV-MV
PWM
E^*
multiple inverters daisy chained

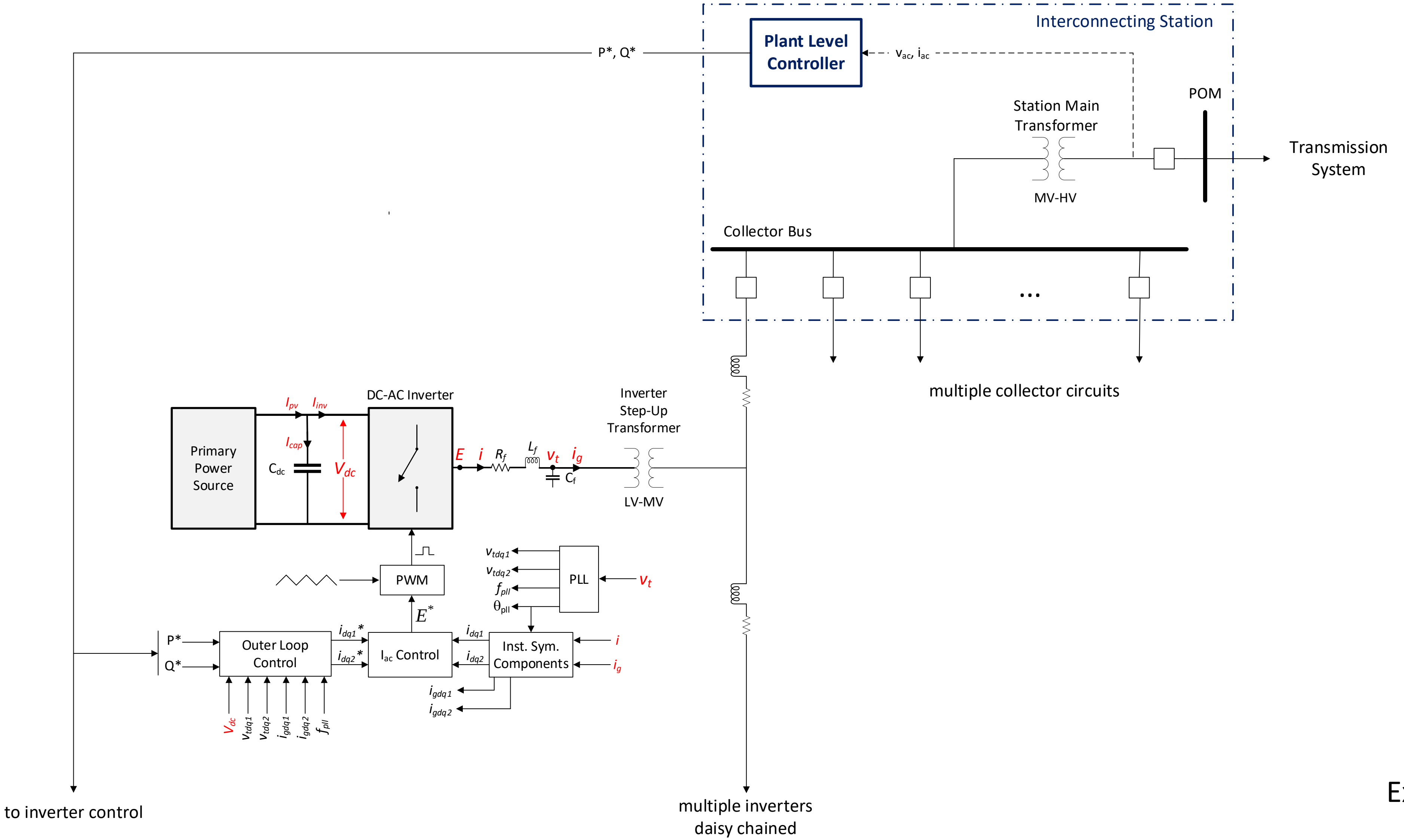
Inverter + inverter control

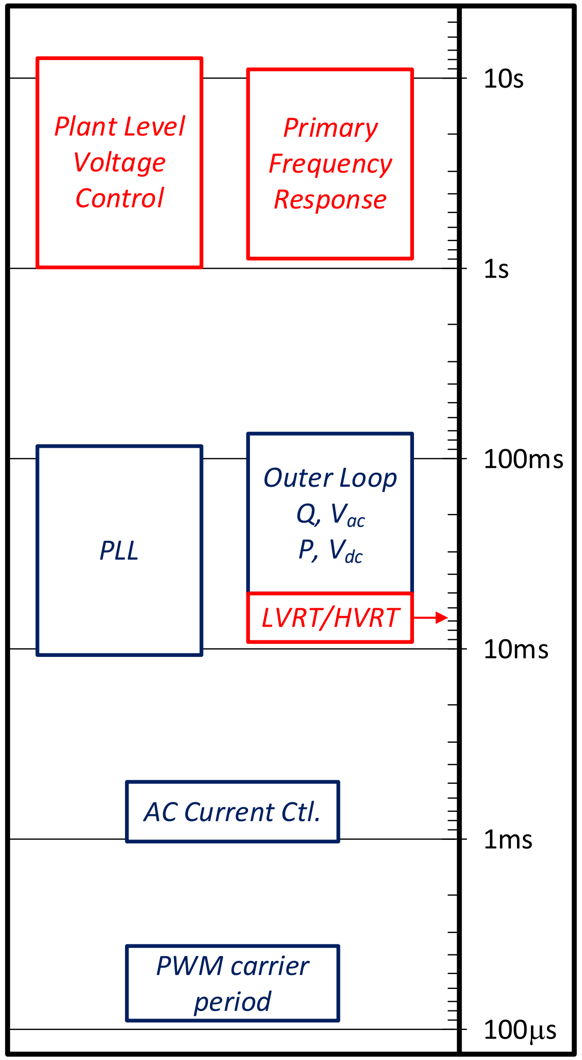


Inverter + inverter control + plant level control



Inverter + inverter control + plant level control—time frames





Example response times of different layers of control [8]

Applicable IBR Standards

Complementing North American Reliability Standards

		Performance	Test & Verification & Model Validation
FERC / NERC?	**Transmission**	• FERC Orders • NERC Reliability Standards & Guidelines	•NERC compliance monitoring & enforcement
	Sub-Transmission	• *IEEE 1547 for all Non-IBRs and for some IBRs on radial systems* ***IEEE 2800-2022 for IBRs***	• *IEEE 1547.1 for all Non-IBRs and for some IBRs on radial systems* ***IEEE P2800.2 for IBRs***
NARUC / State PUCs?	**Distribution** (for DERs)	• IEEE 1547-2018 • IEEE 1547a-2020 ✓	•IEEE 1547.1-2020 •Ul 1741 (SB) •IEEE ICAP ✓

IBRs: Inverter-Based Resources

DERs: Distributed Energy Resources

IEEE 2800/1547 Applicability Matrix can support the responsible entity in their decision by describing the adequacy of the IEEE Stds technical minimum requirements for subtransmission connected IBRs.

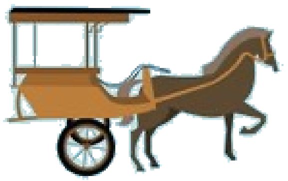
Capability versus Utilization

Capability:

"Ability to Perform"

Scope of IEEE 2800

- Functions
- Ranges of available settings
- Minimum performance specifications



Examples

- Frequency Response
  - Primary frequency response
  - Fast frequency response
- Ride-Through
  - Voltage ride-through
  - Current injection during ride-through
  - Consecutive voltage ride-through
  - Frequency ride-through
  - ROCOF ride-through
  - Phase angle jump ride-through

Utilization of Capability:

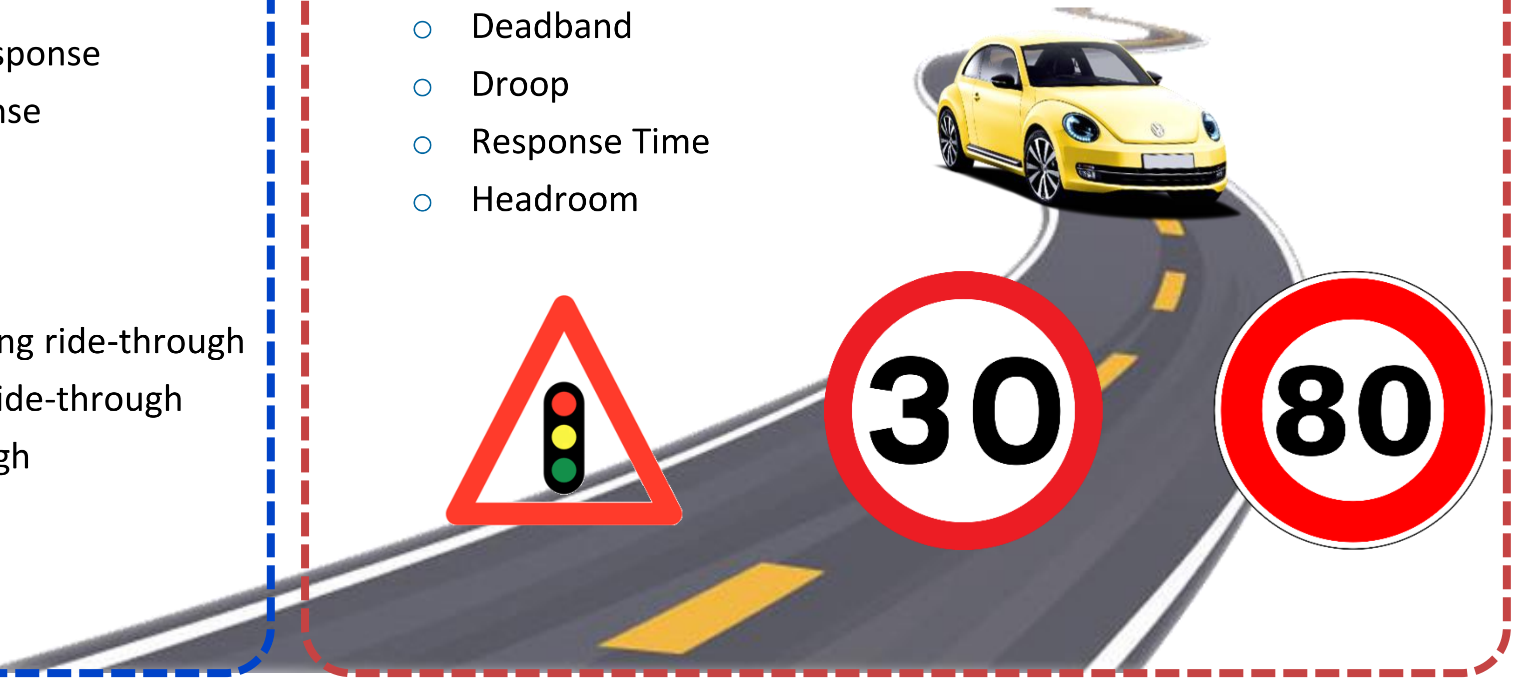
"Delivery of Performance"

Scope of Interconnection or Ancillary Services Agreement

- Enable/disable functions
- Functional settings / configured parameters
- Operate accordingly (e.g., maintain headroom, if applicable)

Examples

- Deadband
- Droop
- Response Time
- Headroom



IEEE 2800-2022 Technical Minimum Capability Requirements

TS owner can require additional capability

Raising the minimum bar

Capability Required in IEEE 2800

General Requirements

“shall have”

- Measurement accuracy
- Controls Prioritization
- Control responses
- Applicability to Diverse IBR Plants

Frequency Response

- Fast Frequency Response for under-frequency conditions — **“may” for over-frequency conditions**
- Primary Frequency Response

Reactive Power – Voltage Control

- Q for voltage control at zero active power — **Ac-connected offshore wind: “should have”**
- Automatic Voltage Regulation Functions
- Reactive Power

Power Quality

TS owner “should” specify

- Harmonic Voltage Limitations
- Prevent Transient Overvoltage
- Harmonic Current Limitations
- Phase Unbalance
- Rapid Voltage Change
- Flicker Limitations

Ride-Through Capability and Performance, Protection

- Unbalanced Current Injection
- Balanced Current Injection
- Voltage Ride-through including TrOV + Consecutive
- Frequency & Phase-jump Ride-through
- Coordination Of Protection

Modeling & Validation, Measurement Data, and Performance Monitoring

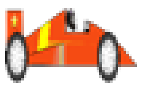
- Process and criteria for model validation
- High Fidelity Performance Monitoring
- Validated Models

Tests and verification requirements

- Post-commissioning Monitoring
- Plant-level Evaluation & Modeling
- Commissioning Tests
- Type tests

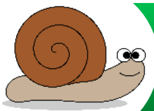
Requiring *All* Capabilities May Conflict with *Current* Market Rules

Inventory of Utility Approaches for IEEE 2800 Adoption



General Reference

- Florida Power and Light (FPL)
- Salt River Project (SRP)[2]
- Southwest Power Pool (SPP)[7]



Detailed Reference

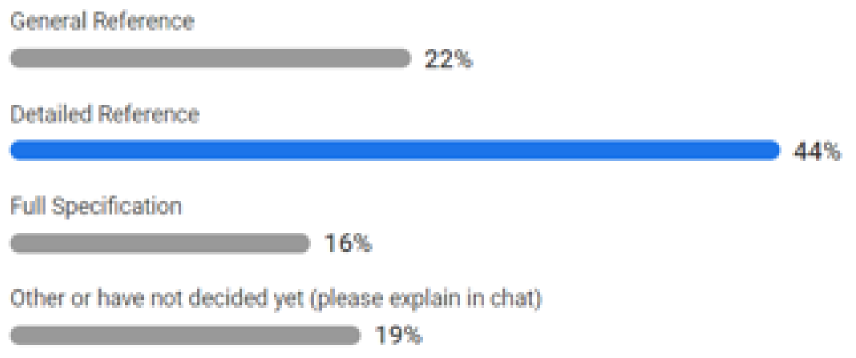
- Duke Energy[4]
- ISO New England[1]
- MISO[5]
- New York ISO[3]
- Southern Company[1]

Full Specification

- ERCOT [2]
- Ameren IL [6]

Live Poll: Which adoption approach are you considering? 32

(based on February 15, 2023 webcast: link)



- Other utilities/ISOs considering IEEE 2800-2022 adoption: AESO, BPA, Great River Energy, Long Island Power Authority, Manitoba Hydro, TVA

[1]: Presented on November 15, 2022 webcast: link
[2]: Presented on February 15, 2023 webcast: link
[3]: Presented on March 15, 2023 webcast: link
[4]: Presented on April 12, 2023 webcast: link
[5]: Presented on May 17, 2023 webcast: link
[6]: Presented on June 14, 2023 webcast: link
[7]: Presented on September 20, 2023 webcast: link

Relationship of Performance Requirements and Model Development

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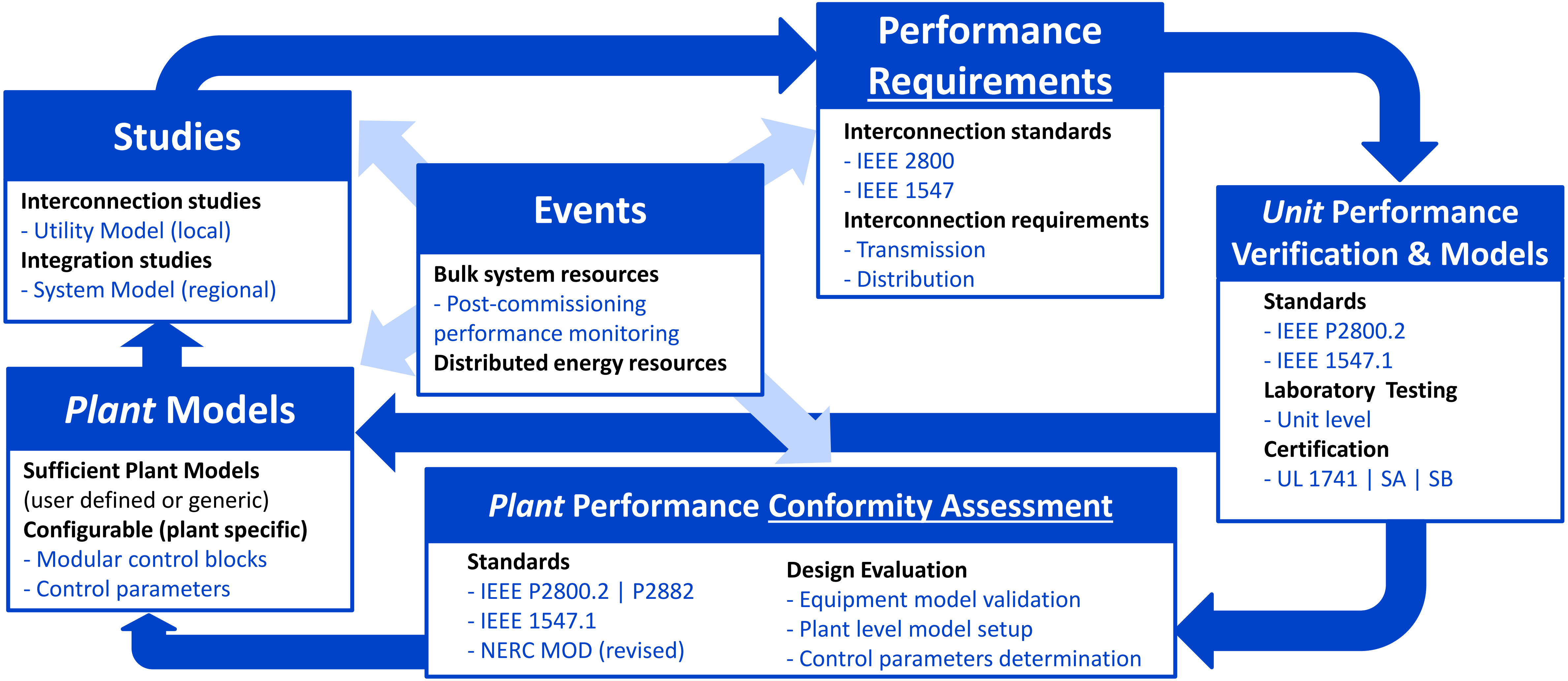
Models and Performance Requirements Are Interrelated



Industry-Wide Collaboration and Continuation of
Plant-Level Model Development, Improvement, and Validation of Inverter-Based DERs

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9:30 a.m. **Generic IBR Positive Sequence Models for Solar PV and Storage**
Deepak Ramasubramanian

10:20 a.m. **Break (time for some Q&A)**

10:40 a.m **Generic EMT Model for Solar PV and Storage conforming with IEEE 2800-2022**
Deepak Ramasubramanian

11:10 a.m. **Potential Use Cases of Generic Models to Generate Reference Traces for Plant-Level Conformity Assessment in the Interconnection Process**
Jens Boemer

11:40 a.m. **High-level review of DER Modeling for Transmission Planning Studies**
Jens Boemer

11:45 a.m. **Additional Q&A / Overflow**

Few basics about various inverter mathematical models

Generic model	Does not always imply	Bad model
User defined model from manufacturer	Does not always imply	Good model
RMS/Positive sequence model	Does not always imply	Bad model
Electromagnetic transient (EMT) model	Does not always imply	Good model

- All mathematical models have limitations
- When using mathematical models, few questions to be asked:
  - Is this the appropriate type of model for the study that is to be done?
  - Is the model being used in a correct manner?
  - Are all relevant components/control loops, that matter for the study, modeled?
  - Is the model appropriately parameterized?
  - Are sufficient validation results of model behavior available?

Inverter Based Resource (IBR) Positive Sequence Models

- The most recent publicly available renewable energy system (RES) models are the 2nd generation generic models developed through the WECC REMWG effort

- They allow for modeling:
  - Wind Turbine Generators (WTG)
  - Photovoltaic (PV) Generation
  - Battery Energy Storage Systems (BESS)
  - Complex plants RES plants

- IEC TC88 WG27 standard models are very similar, but slightly more detailed; the plant-level models not yet completed

- *Model User Guide for Generic Renewable Energy System Models.* EPRI, Palo Alto, CA: 2023. Product ID: 3002027129 (link)
- P. Pourbeik, J. Sanchez-Gasca, J. Senthil, J. Weber, P. Zadehkhost, Y. Kazachkov, S. Tacke and J. Wen, “Generic Dynamic Models for Modeling Wind Power Plants and other Renewable Technologies in Large Scale Power System Studies”, *IEEE Trans. on Energy Conversion, September 2017.*

Advantage of Generic Models

- **Validation:** numerous validation cases demonstrated

- **Portability across software platforms:** implemented and tested in major commercial tools, and consistent across the tools

- **Transparency & Documentation:** standard, generic, public and open with documentation/specifications that are available to all

- **Publicly Available:** avoid this issue of being able to share models.

- **Modeling the Future:** generic models are useful for performing futuristic studies where the actual equipment to be used is not yet known

Limitations of Generic Models

- **Positive-sequence:** cannot be used for accurate assessment of unbalanced conditions.

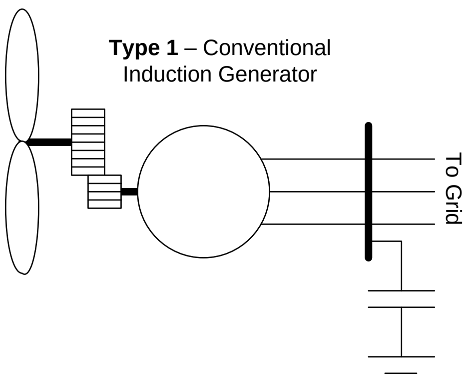
- **Typical range of stability studies:** consider dynamics in the typical range of stability studies (0.1 – 3 Hz); all other models are only truly good within this range of frequencies. The control loops within the models (e.g. closed-loop voltage control) may also consider frequencies ranging up to 10 Hz.

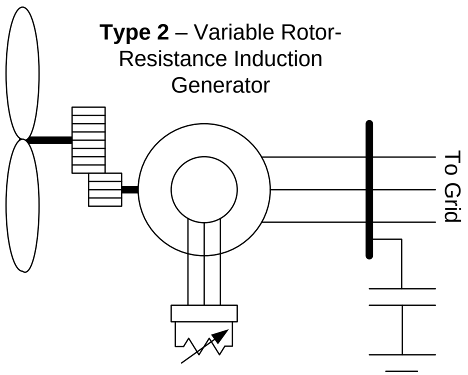
- **Constant wind speed/ solar irradiation:** the generic models assume that wind speed (and solar irradiation) is constant during a stability simulation.

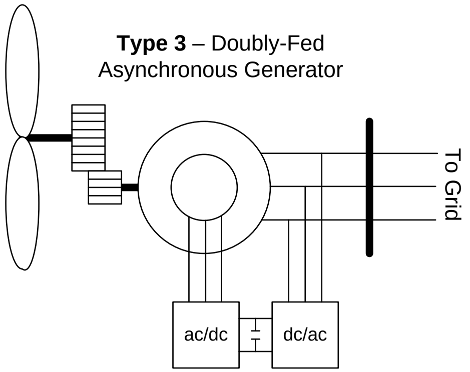
- **Weak Systems:** not intended for detailed local studies associated with control tuning and design for the interconnection of wind/PV plants to very weak systems (i.e. short-circuit ratios below approximately 2 or 3)

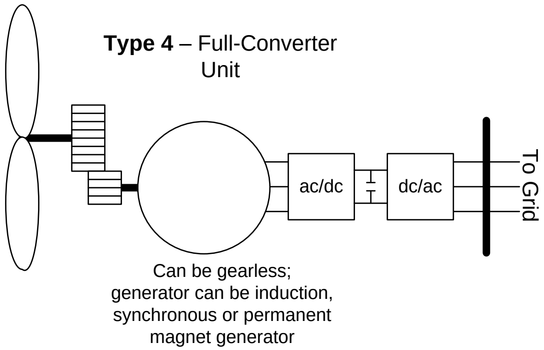
- **Specialized Studies:** The models cannot be used for detailed studies that relate to phenomena such as potential torsional interactions between the wind turbine generator and the electrical power system (e.g. nearby series capacitor).

Renewable technologies represented by generic models







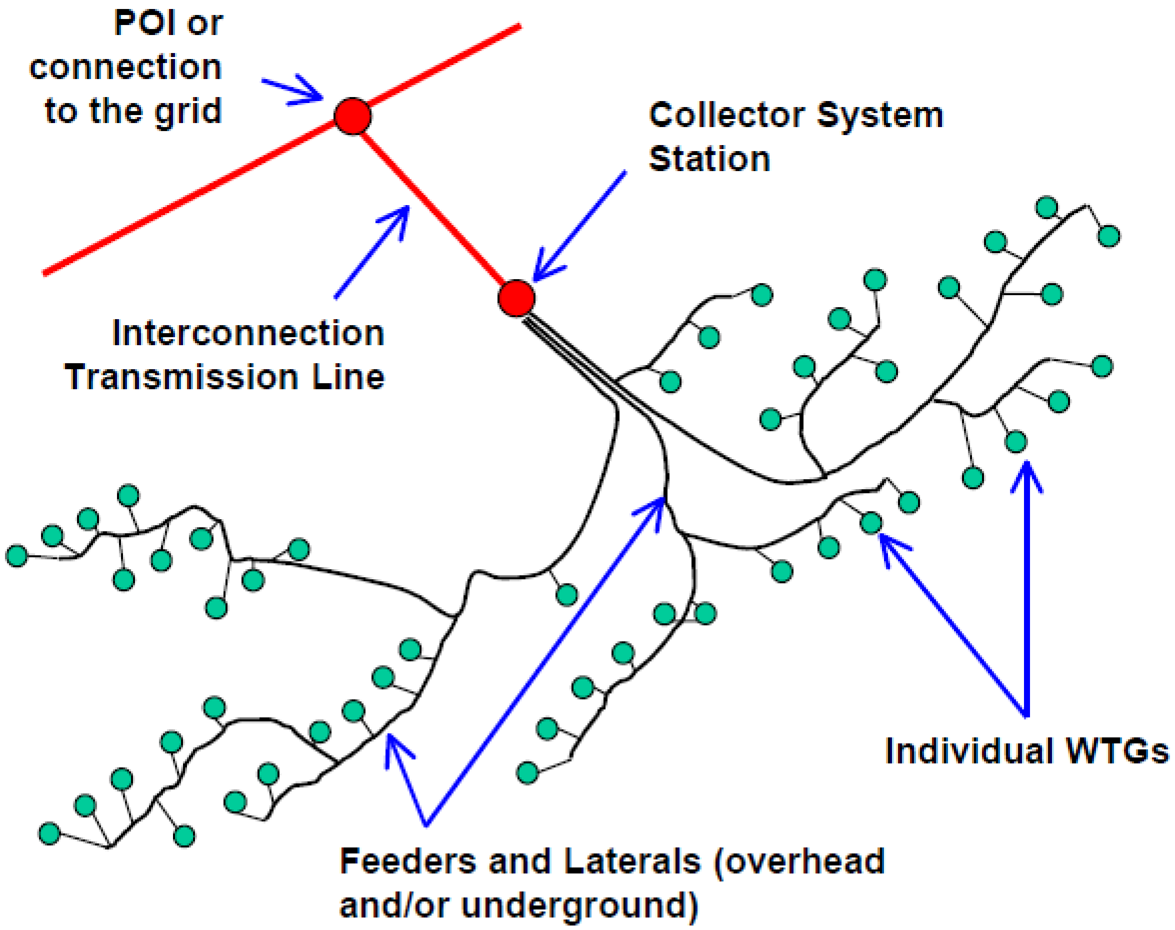


Type 5 Wind – synchronous generator + variable speed mechanical gear

PV – photovoltaic + inverter

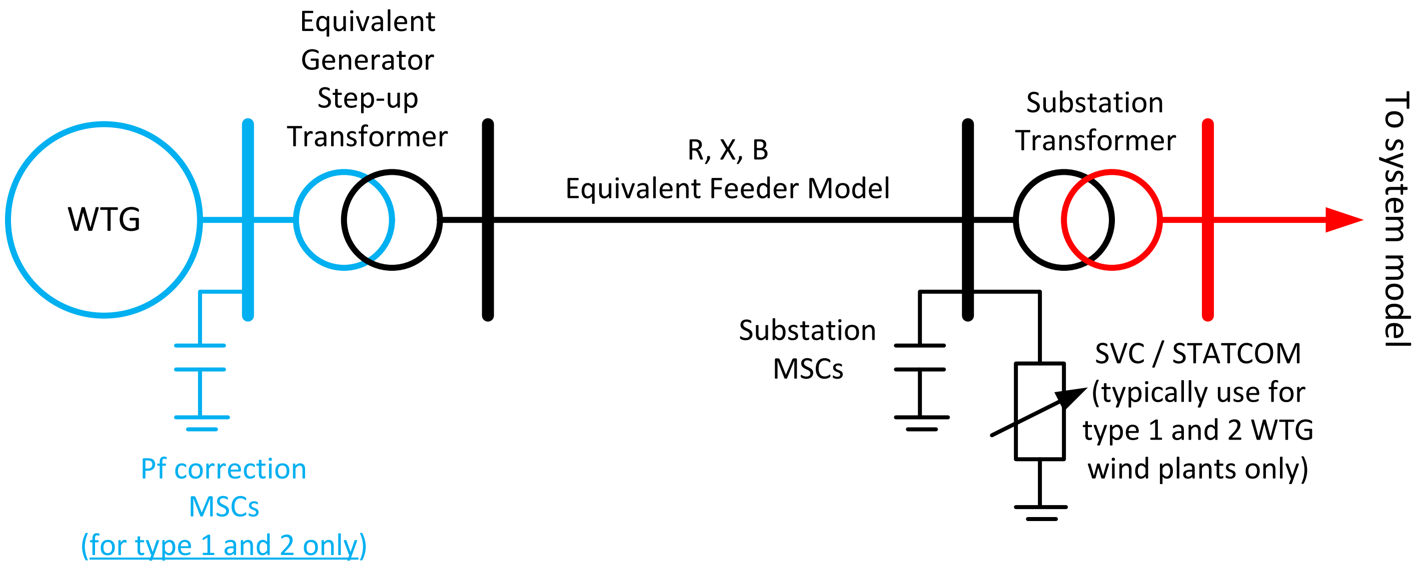
BESS – battery energy storage; again inverter interface

Example Wind Power Plant Topology



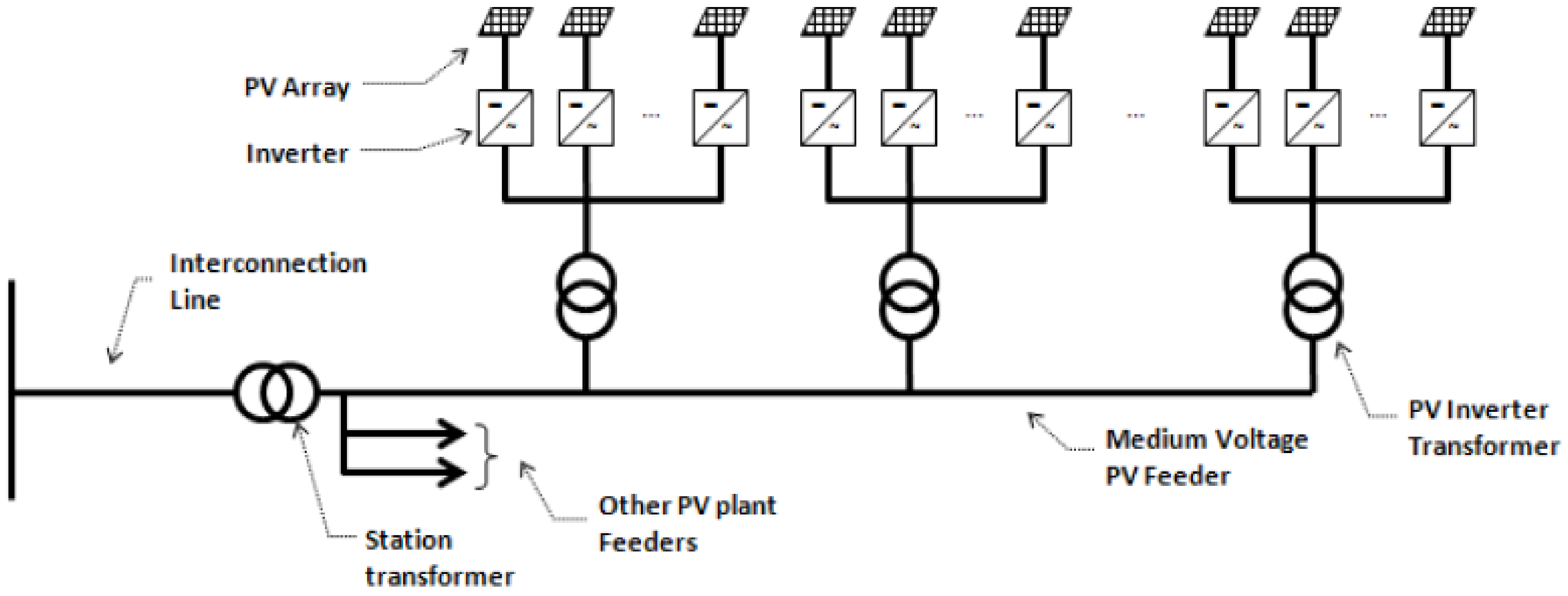
Source: WECC Wind Power Plant Power Flow Modeling Guide (https://www.wecc.biz/Reliability/WECC%20Wind%20Plant%20Power%20Flow%20Modeling%20Guide.pdf)

MODELING A WIND OR PV POWER PLANT



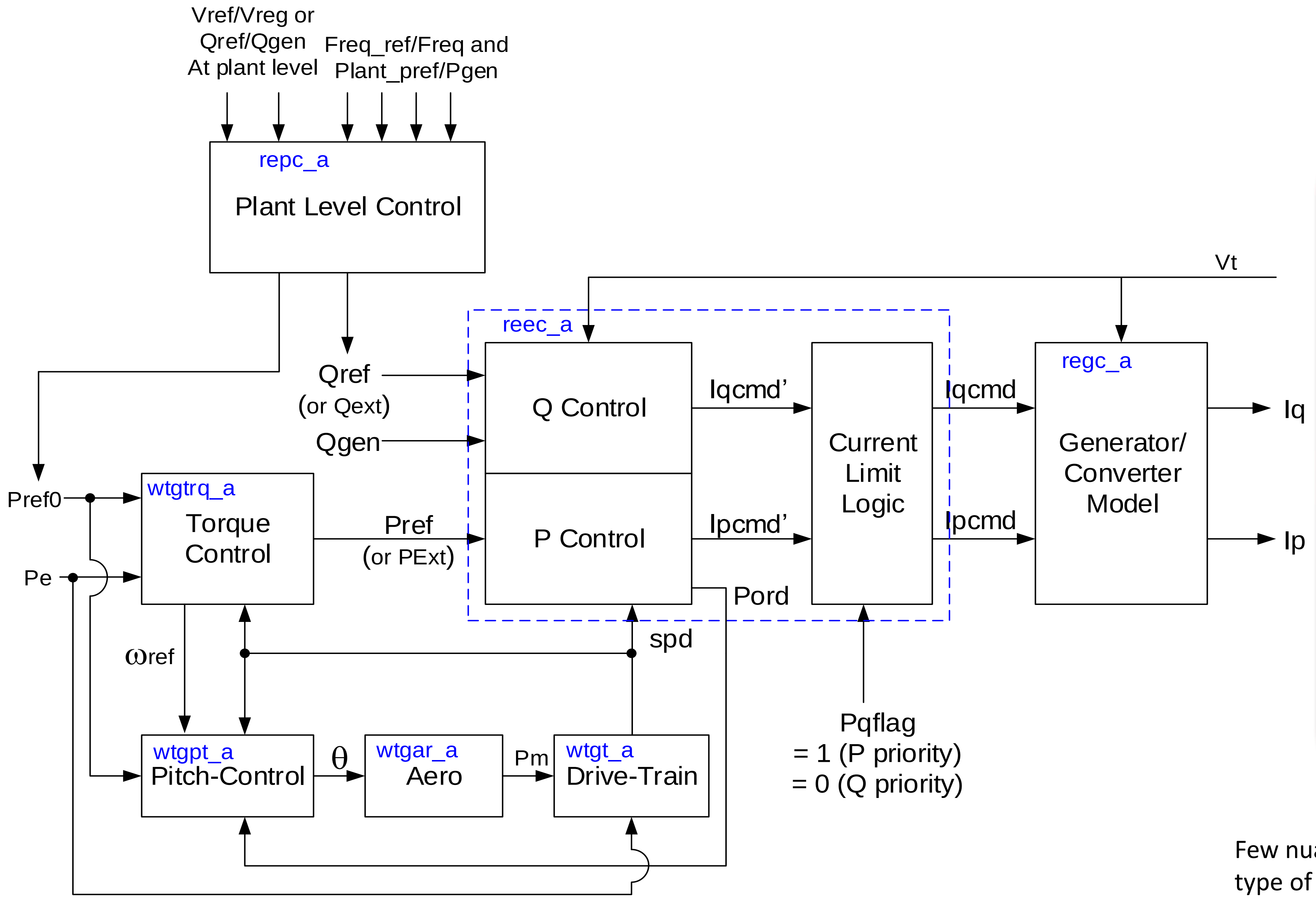
- If type 1 or 2 WTG, explicitly model switched shunt capacitors at generator terminals
- If SVC / STATCOM exists at PCC then model explicitly using SVSMO1 or SVSMO3, respectively
- Approach for developing single equivalent feeder model explained is explained in the NREL paper (https://www.wecc.biz/Reliability/WECC%20Wind%20Plant%20Power%20Flow%20Modeling%20Guide.pdf)

Example Solar Power Plant Topology



Source: WECC Guide for Representation of Photovoltaic Systems in Large Scale Load Flow Simulations (https://www.wecc.biz/Reliability/WECC%20PV%20Plant%20Power%20Flow%20Modeling%20Guidelines%20-%20August%202010.pdf)

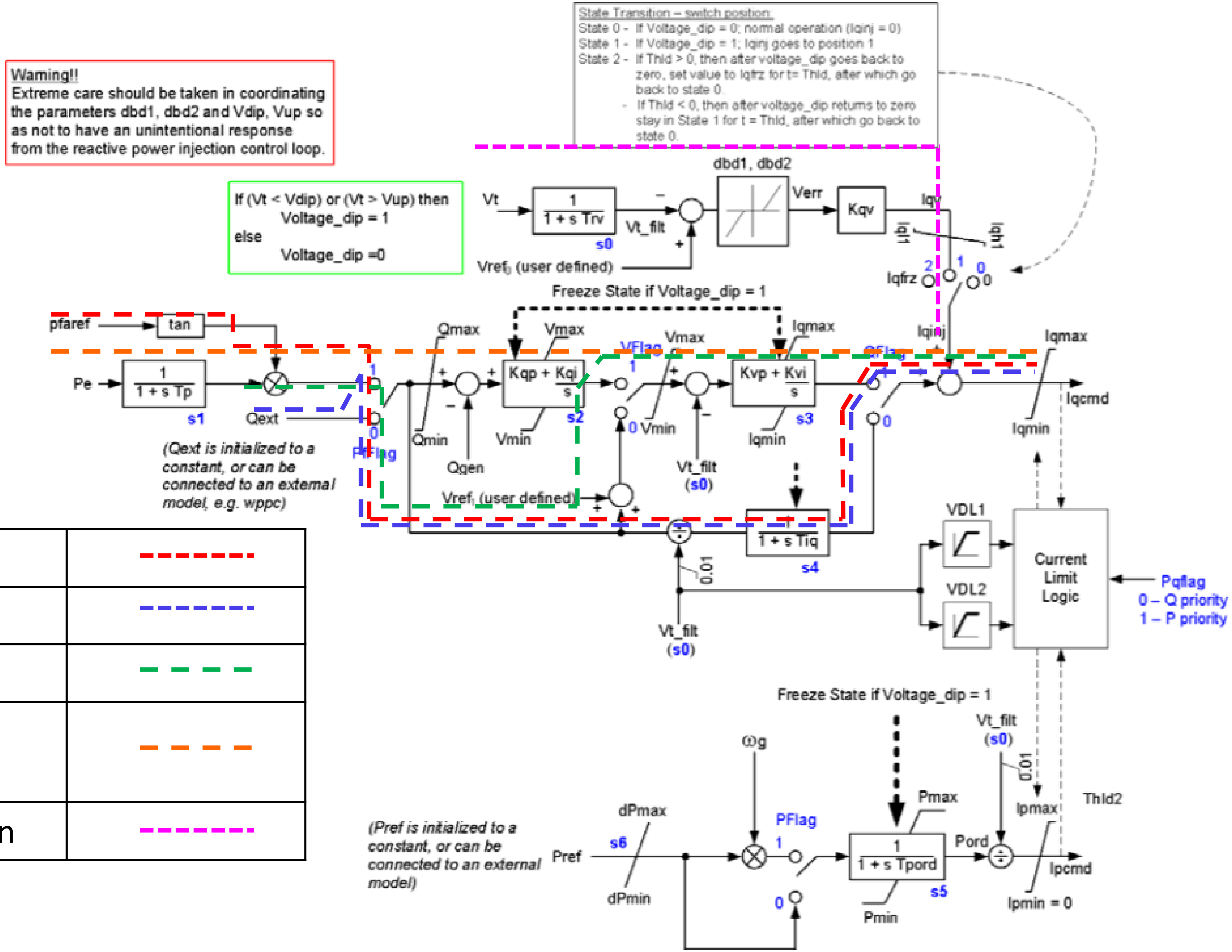
The Building Blocks



Generic models are vendor-agnostic models that do not necessarily represent the exact control algorithm of any particular IBR vendor. When appropriately parameterized, these models can subsequently provide the trend of dynamic behavior expected from IBR plants.

Few nuanced changes to this setup based on type of resource and/or capability of the model

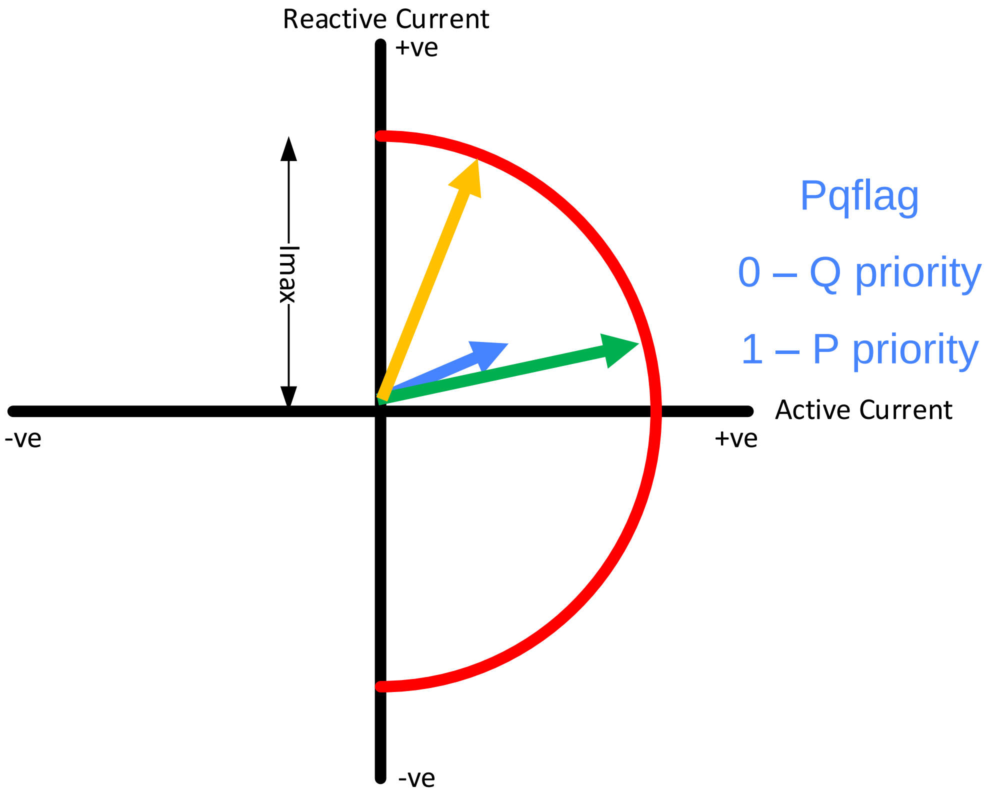
REEC_A



Constant local pf control	red dashed line
Constant local Q control	blue dashed line
Local V control	green dashed line
Local coordinated V/Q control	orange dashed line
Reactive current injection	magenta dashed line

REEC_A – Renewable Energy Electrical Controls A

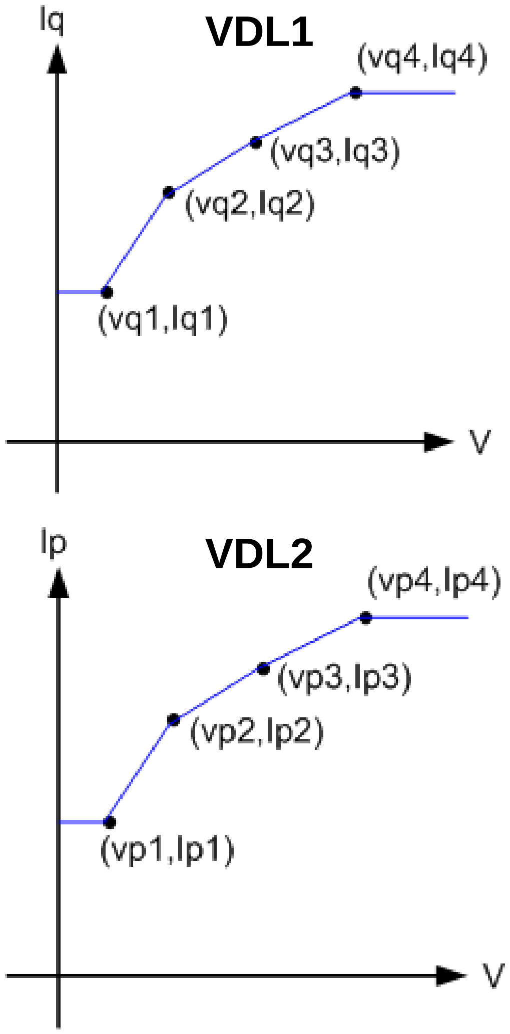
Current Limit Logic



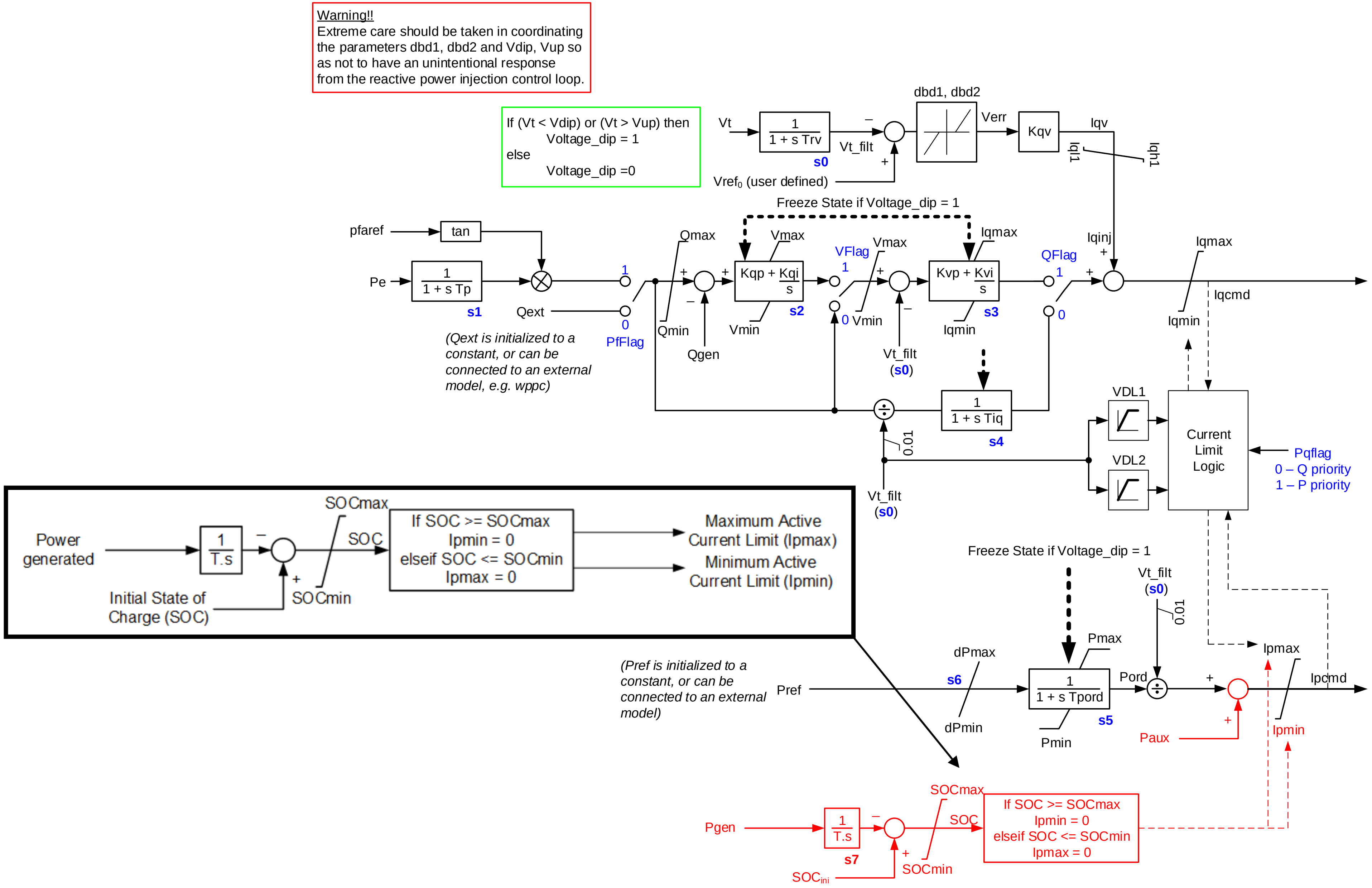
Pqflag

0 – Q priority

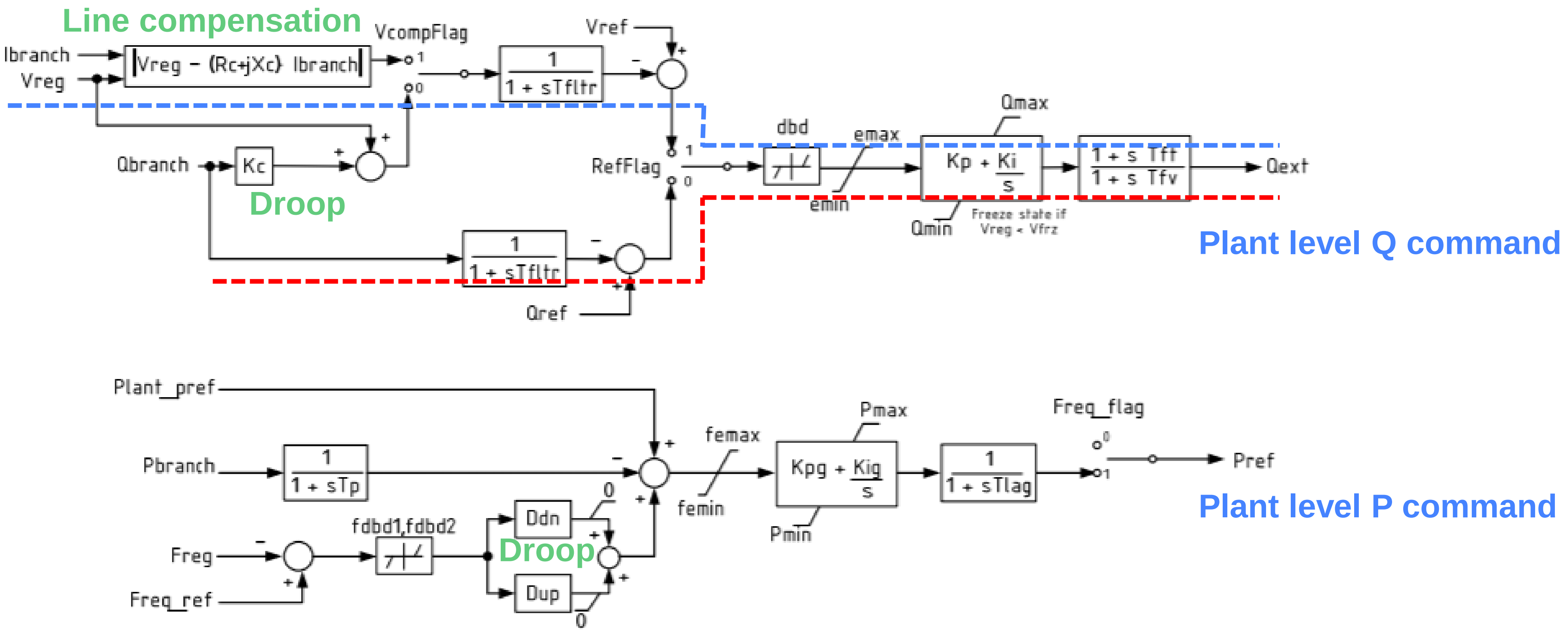
1 – P priority



REEC_C – Renewable Energy Electrical Controls C



REPC_A

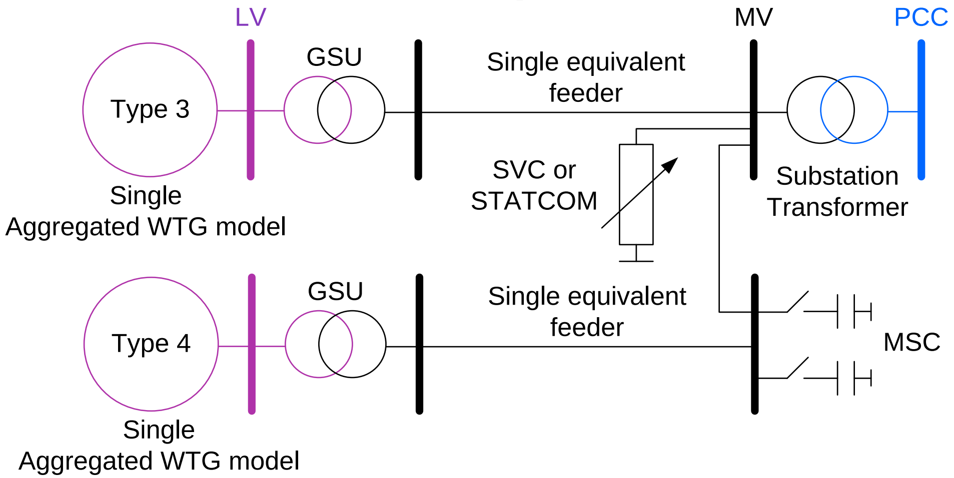

Line compensation
VcompFlag
Vref
Ibranch
Vreg
|Vreg − (Rc+jXc) Ibranch|
1 + sTfltr
Qbranch
Kc
Droop
RefFlag
dbd
emax
emin
Qmax
Qmin
Kp + Ki/s
1 + s Tft / 1 + s Tfv
Qext
Freeze state if Vreg < Vfrz
Plant level Q command
1 + sTfltr
Qref
Plant_pref
Pbranch
1 + sTp
Freg
Freq_ref
fdbd1,fdbd2
Ddn
Dup
Droop
femax
femin
Pmax
Pmin
Kpg + Kig/s
1 + sTlag
Freq_flag
Pref
Plant level P command

Summary of control options and flag settings

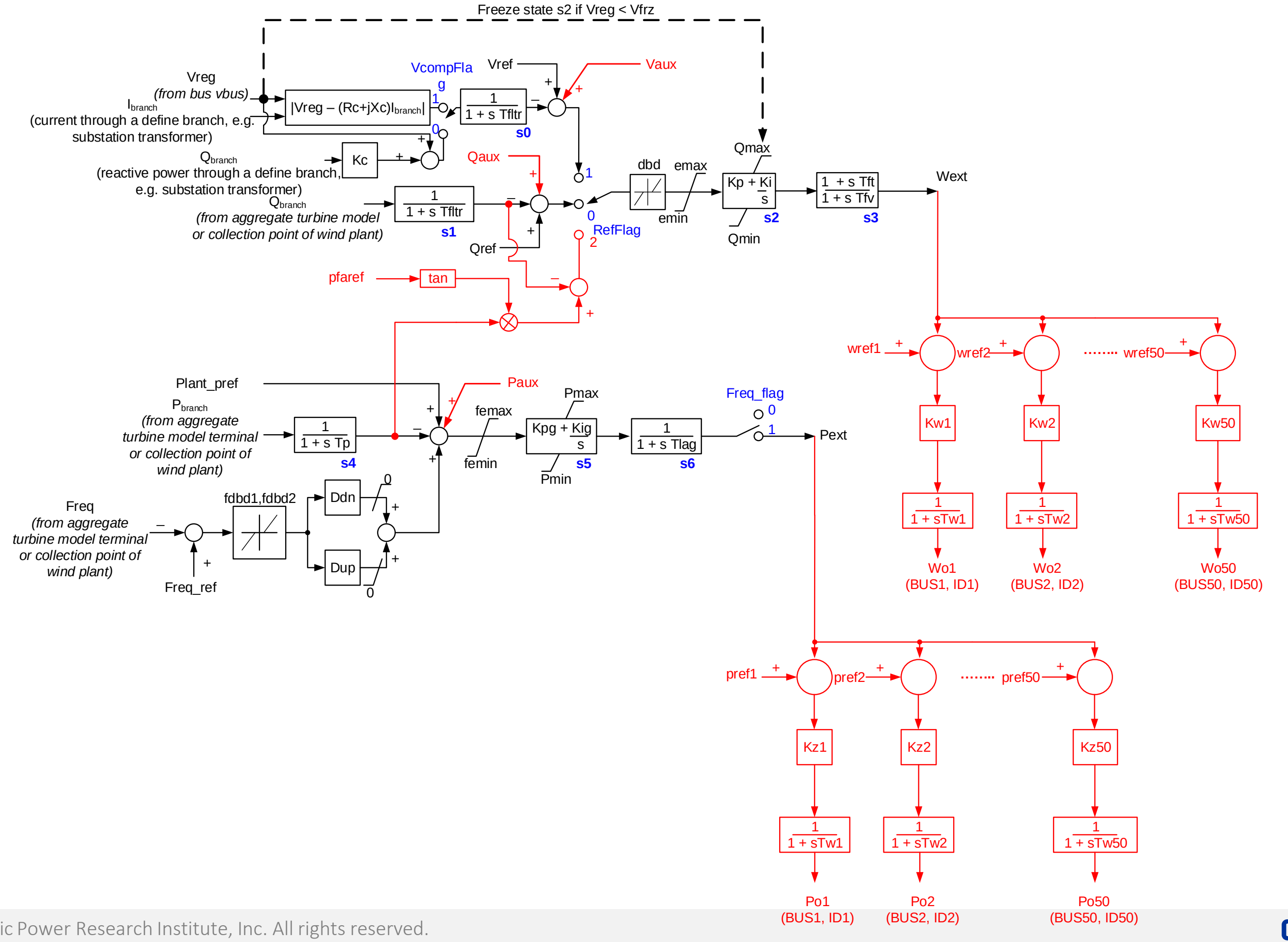
Functionality	Models Needed	PfFlag	Vflag	Qflag	RefFlag
Constant pf control	reec_a	1	N/A	0	N/A
Constant Q control	reec_a	0	N/A	0	N/A
Local V control only	reec_a	0	0	1	N/A
Local coordinated Q/V control only	reec_a	0	1	1	N/A
Plant level Q control	reec_a + repc_a	0	N/A	0	0
Plant level Vcontrol	reec_a + repc_a	0	N/A	0	1
Plant level V Control + coordinated local Q/V control	reec_a + repc_a	0	1	1	1
Plant level Q Control + coordinated local Q/V control	reec_a + repc_a	0	1	1	0

REPC_B – Renewable Energy Plant Controller B

Complex Case



This can also represent a scenario where a battery energy storage is located in tandem with a PV or Wind power plant



Performance of models so far

- Generic models so far can provide reasonable representation of IBR behavior

- There are definite limitations, especially for certain nuanced fault ride through behavior
  - OEM blackbox model should always be used for performance comparison

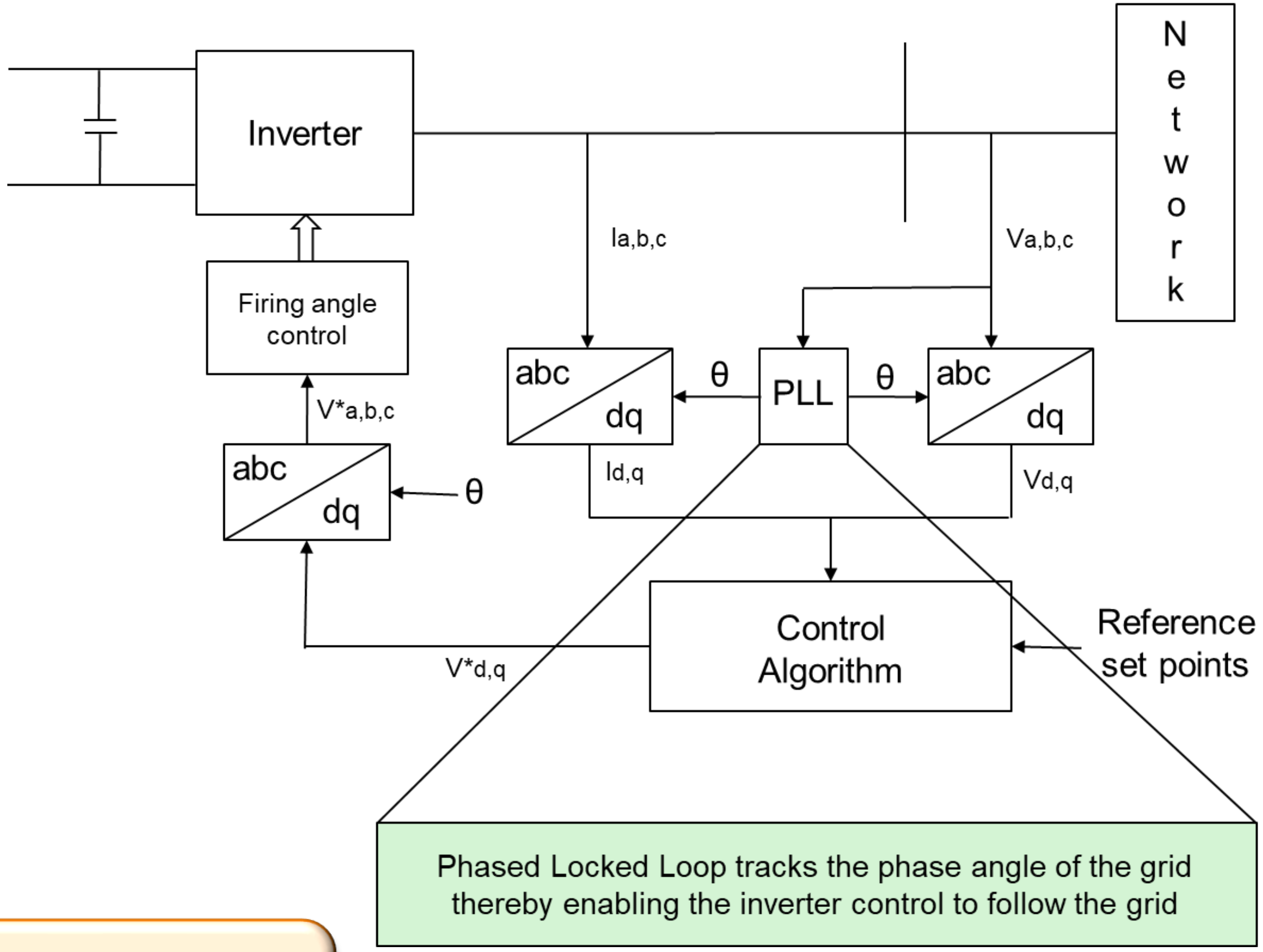
- These limitations may result in OEM models being needed for local studies but generic models for interconnection studies

- Models also have to be improved with increase in IBR percentage

Generic models and low system strength

Basics of present-day IBR – grid interaction…

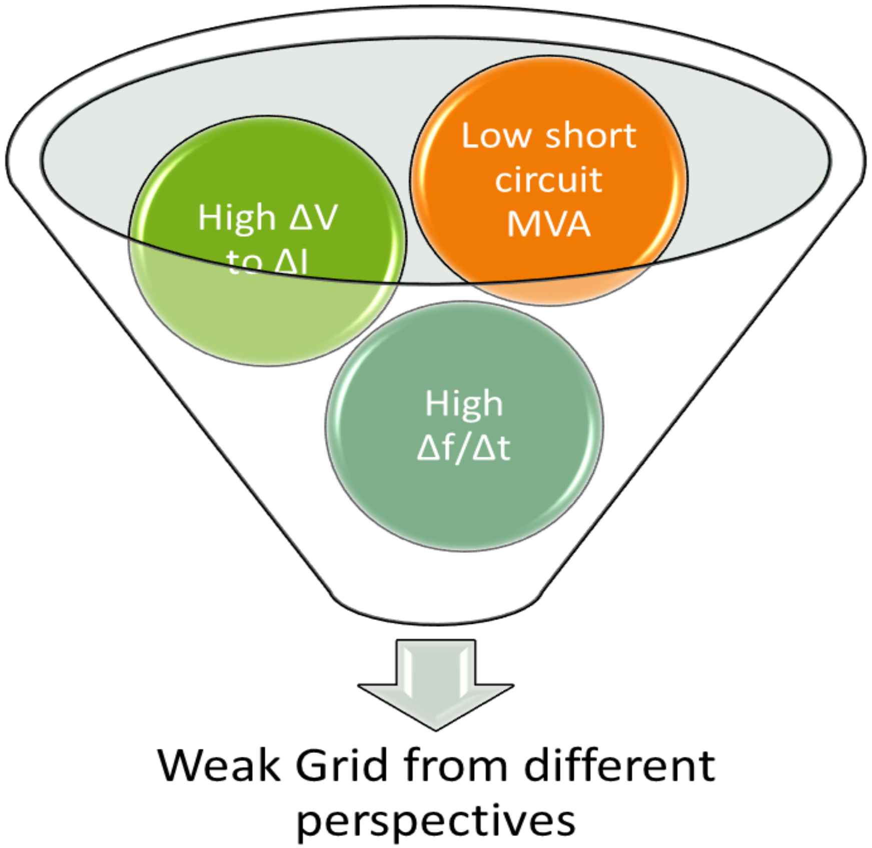
- Unlike synchronous machine, IBR does not have electromagnetic coupling with the grid
  - Conventional IBR uses a Phase Locked Loop (PLL) to remain synchronized and locked to the network.
- All controls within an IBR treat this evaluated PLL phase angle as a reference
  - Subsequently used to evaluate amount of current to be injected by IBR



In synchronous machine, laws of electromagnetics provide grid phase angle

In conventional IBR, specific control loops calculate grid phase angle

Increase in IBR fleet resulting in low short circuit scenarios



An IBR injects controlled current

↓

- In weak grids, for small ΔI, high ΔV:
  - magnitude of change can be large
  - rate of change occurs can be large
  - frequency of change can be high

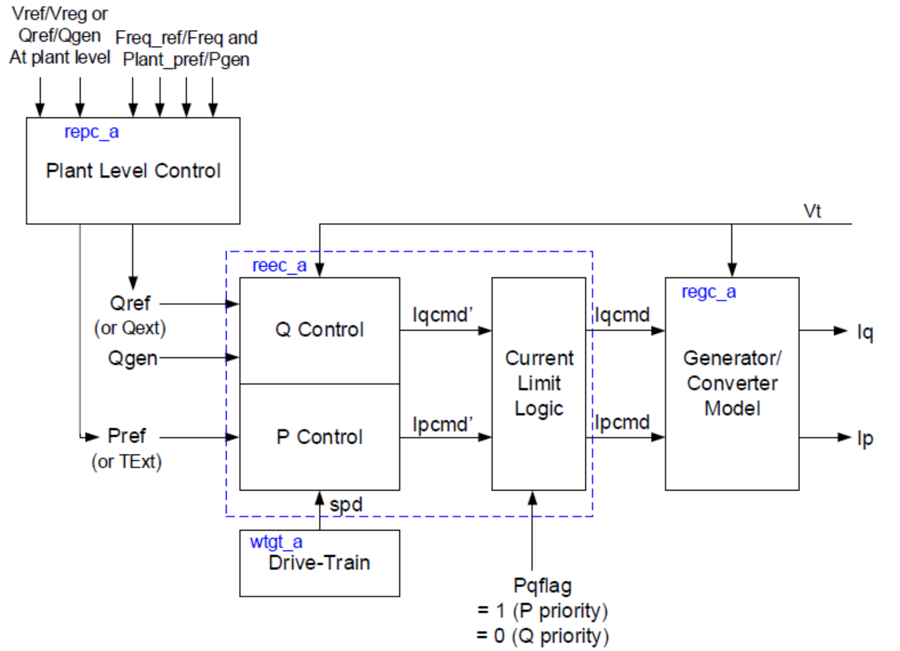
↓

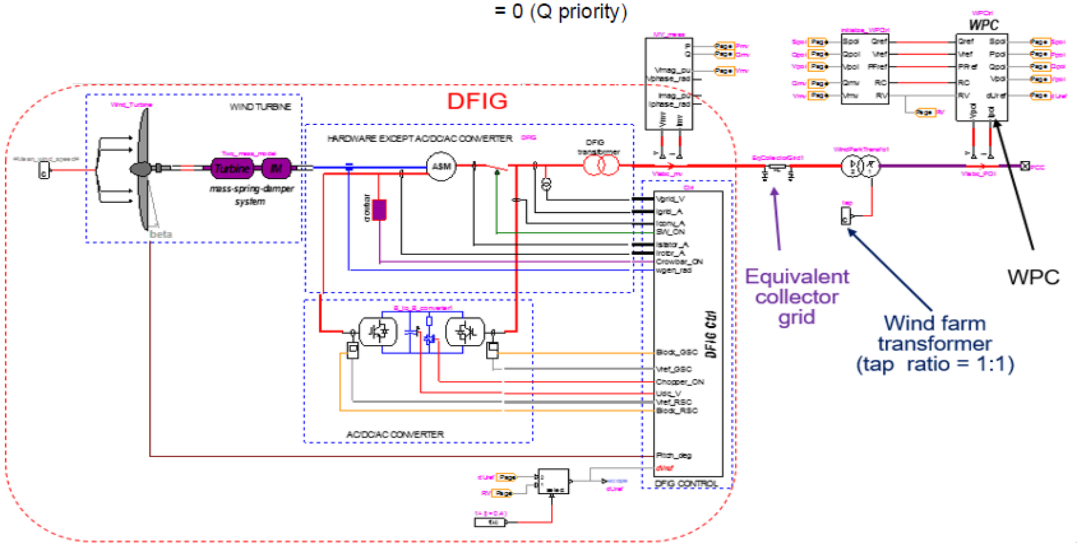
Fast control loops of IBRs can become unstable

- An increasing concern is whether existing positive sequence models can capture this behavior

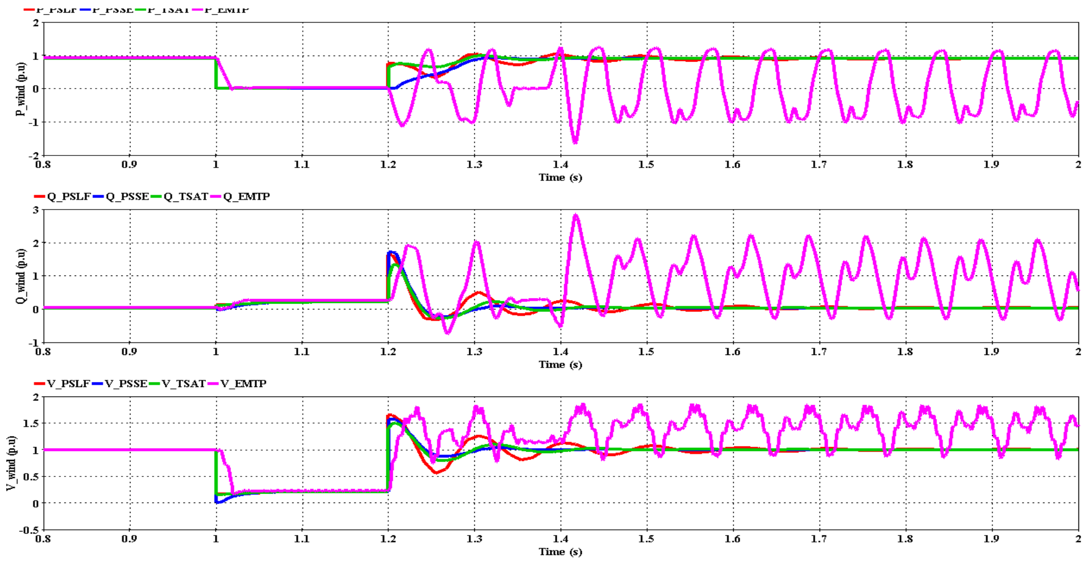
EPRI

Challenges faced by existing positive sequence models in low short circuit conditions

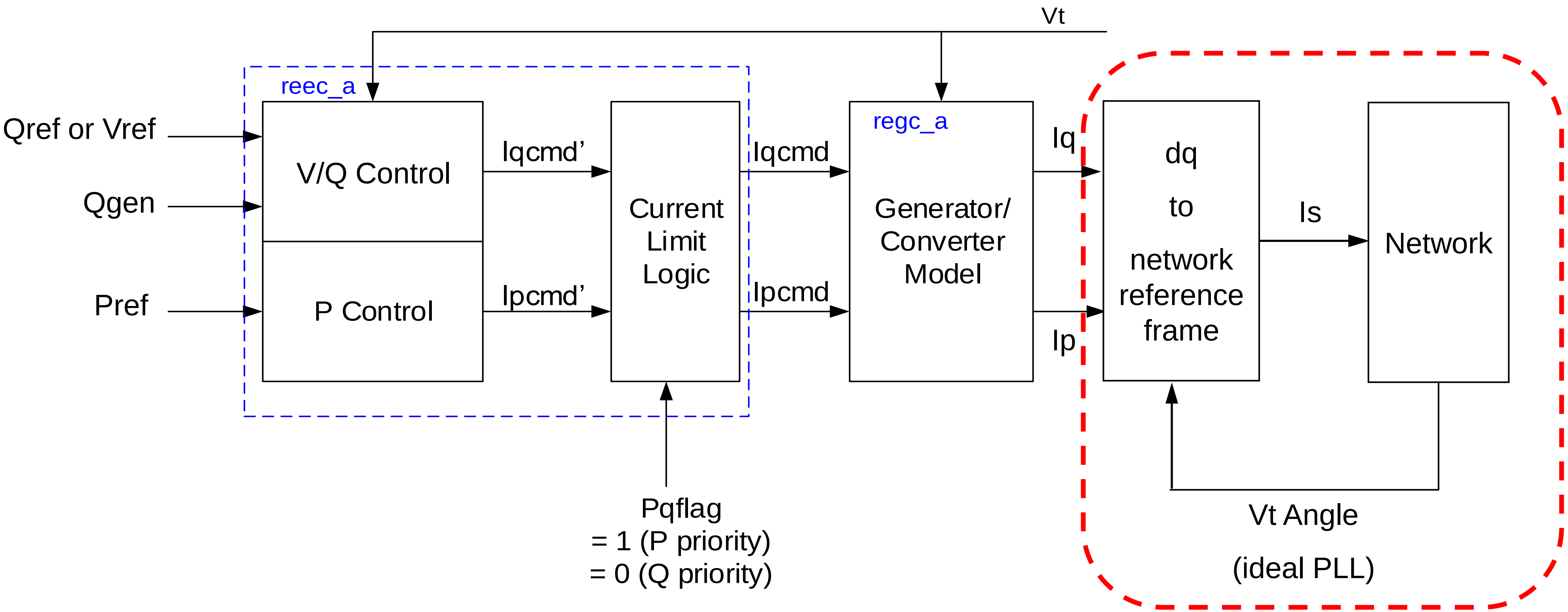




- **Fast controller dynamics/interactions may not be modeled**
- **Advanced control features may not be modeled**
- **Numerical robustness issues may arise**



General interconnection of model to network in positive sequence

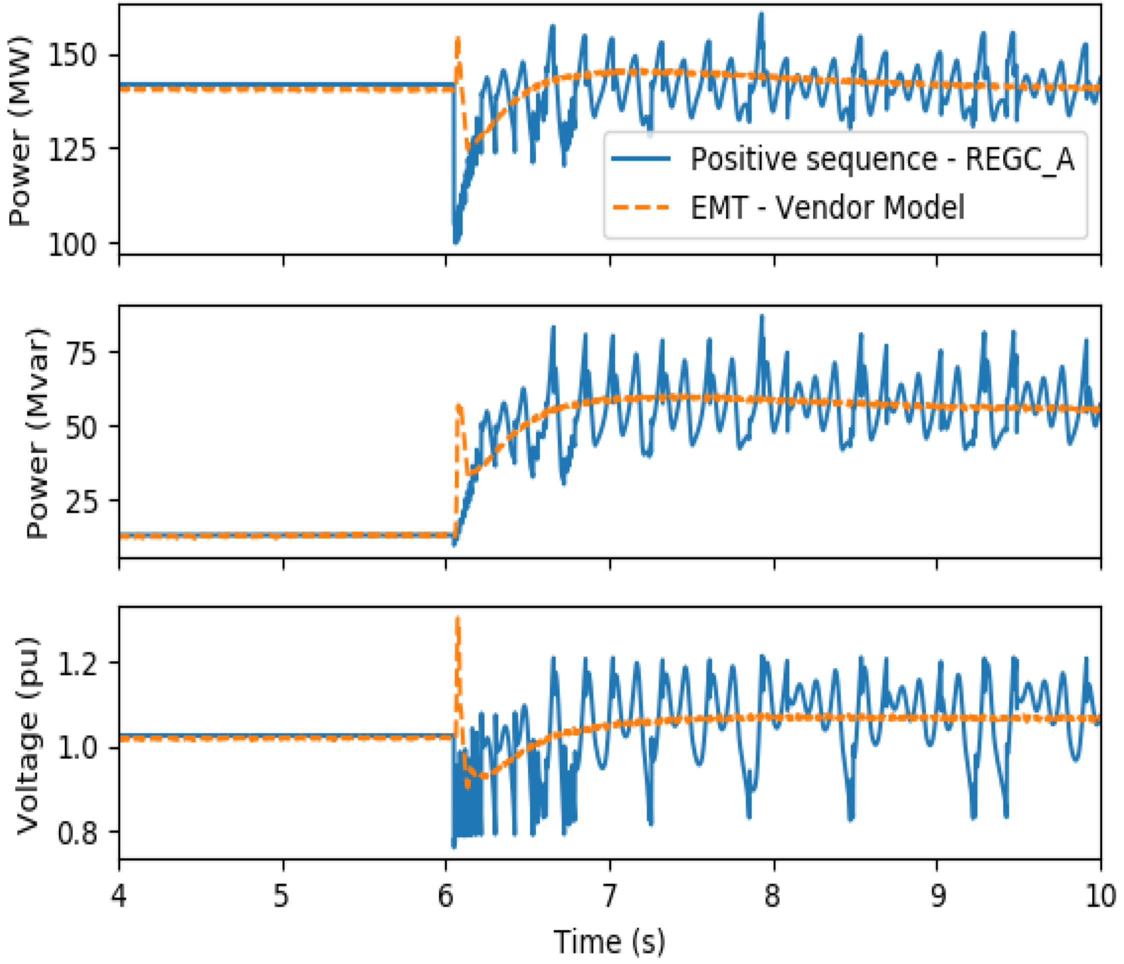


Modeling simplifications and assumptions in positive sequence platforms

- Converter connected as a current source to the network
- Network solver provides the reference angle (voltage angle). No need for explicit representation of PLL
- No modeling of the fast inner-current control loops of the converter
- All converter high-frequency controls (kHz range) are simplified and modeled as algebraic equations

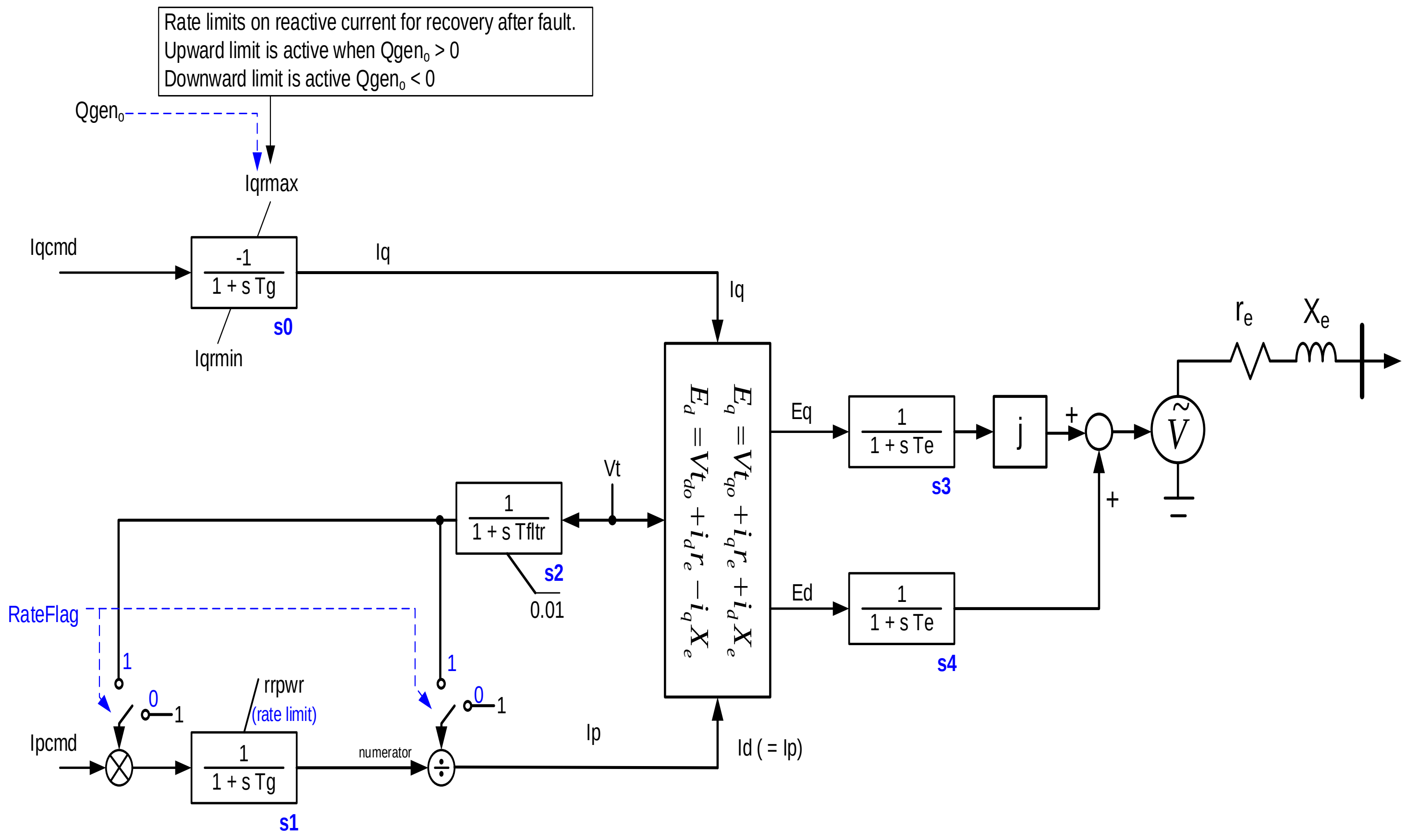
Performance of existing REGC_A model under low short circuit

- Existing state of art generic model in positive sequence simulation software is represented as a current source.
- This model is named as REGC_A
- In low short circuit scenarios, a current source model can encounter numerical robustness obstacles.
- To overcome this obstacle, two new models, both with voltage source representation, have been developed.
  - These models are named as REGC_B and REGC_C

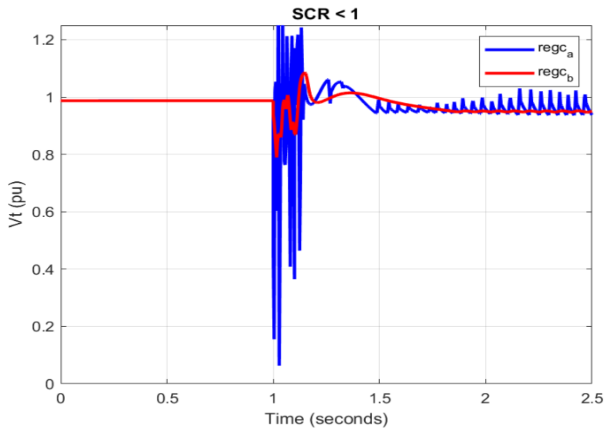


SCR changes from 10 to 2 at 6s

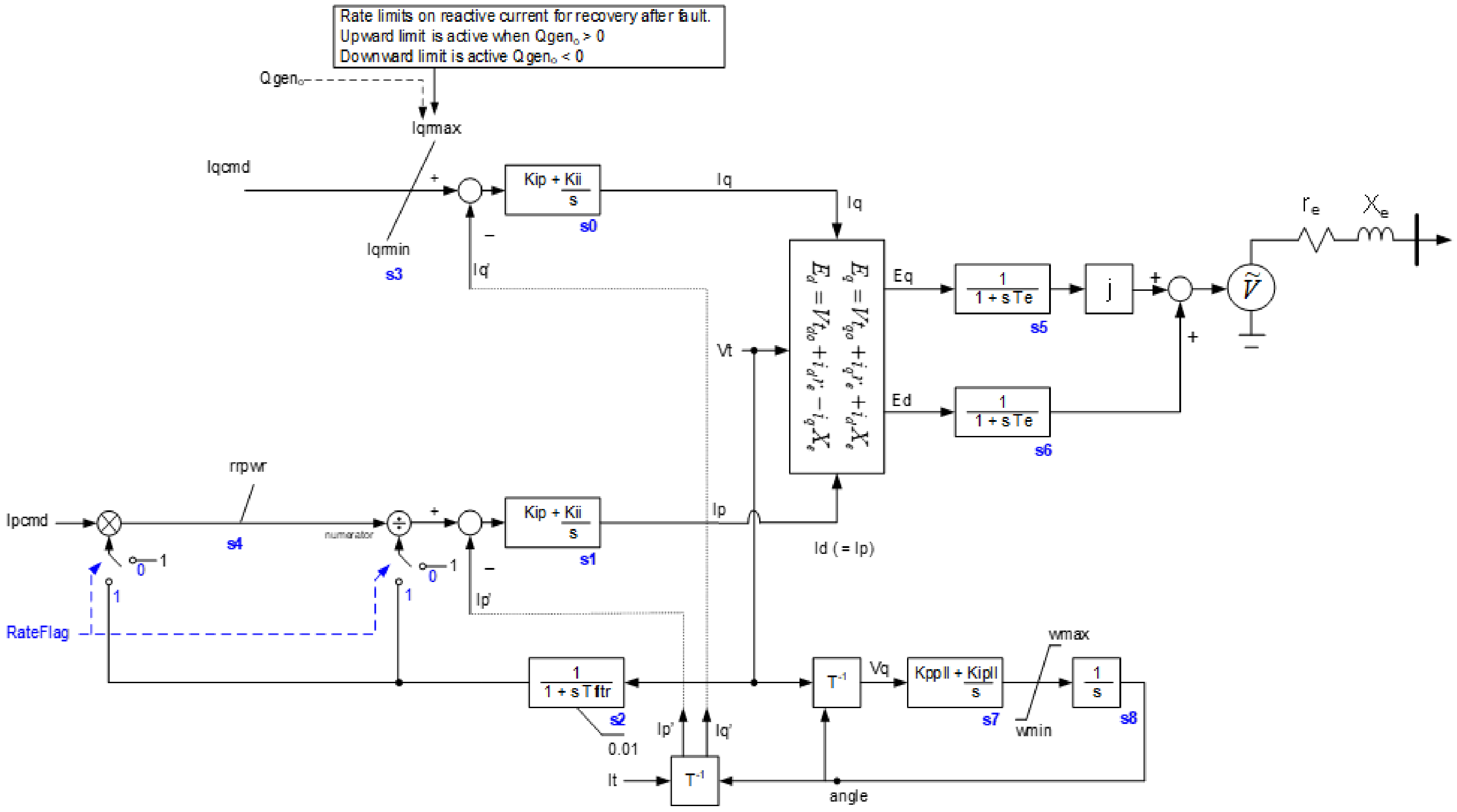
The REGC_B Generic Model



- Assumes near ideal dynamic behavior of
  - inverter's inner current control loop.
  - Inverter's phase locked loop
- Current commands are translated into voltage reference commands behind an impedance

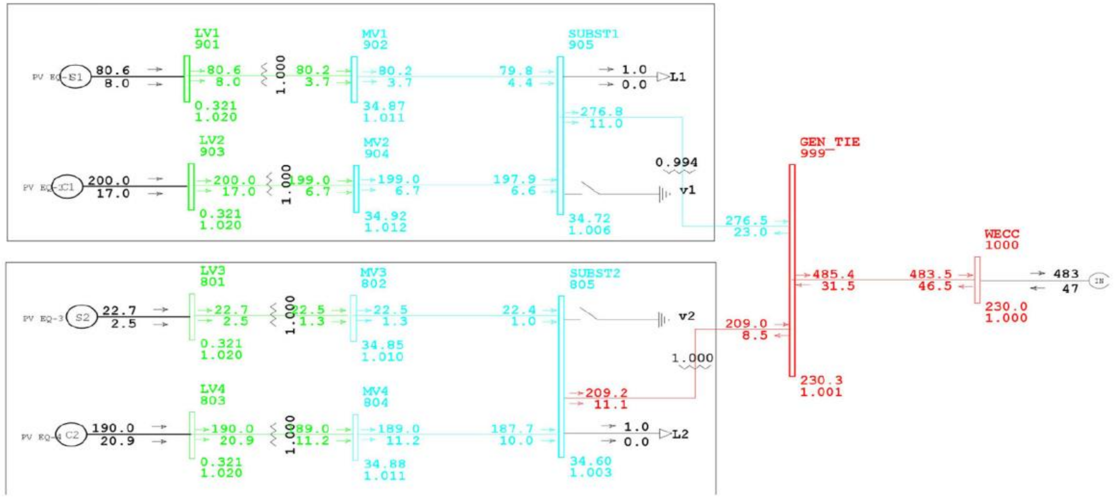


The REGC_C Generic Model



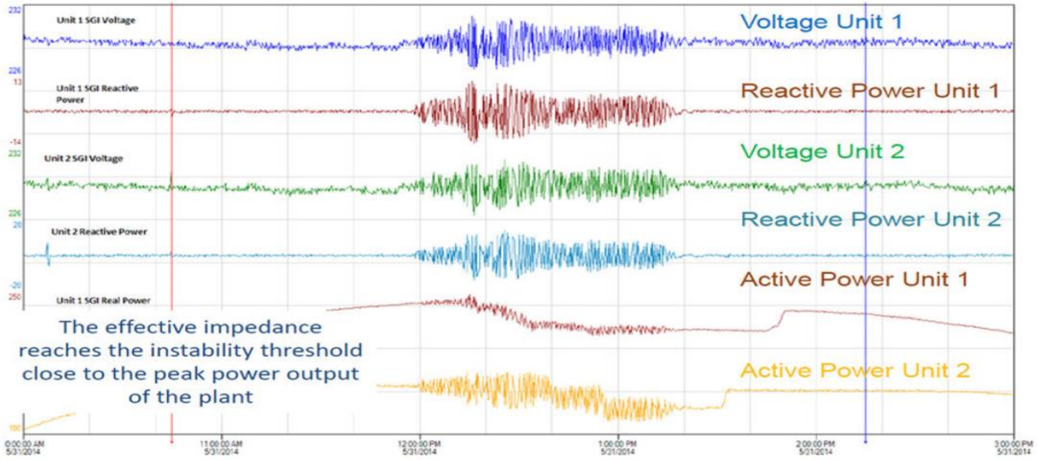
- Approximate representation of dynamic behavior of
  - inverter's inner current control loop.
  - Inverter's phase locked loop
- Current commands are translated into voltage reference commands behind an impedance

Example 1: Recreation of weak grid oscillatory event using REGC_C model



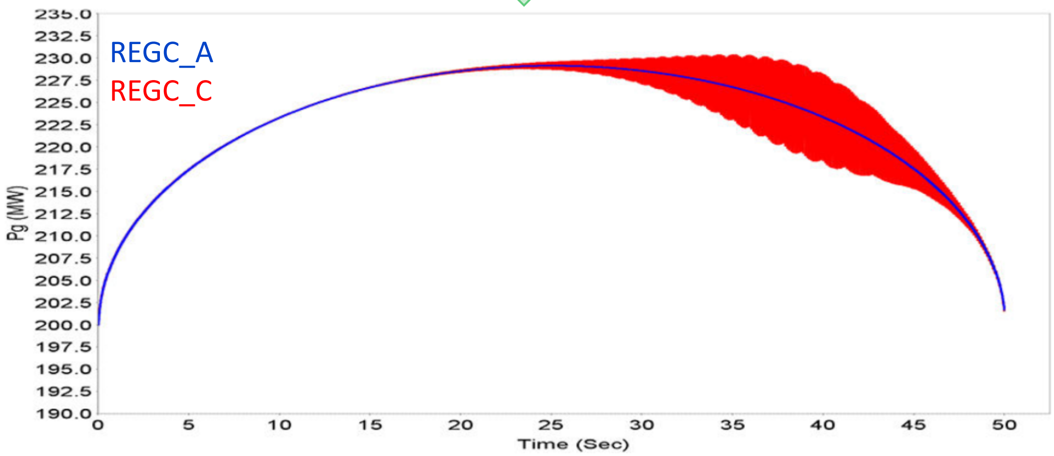
Oscillation occurred as plant output ramps up to maximum

PV Plant – ~7 Hz Oscillation



First Solar Inc.: 'Deploying utility-scale PV power plants in weak grids,' 2017 IEEE Power & Energy Society General Meeting, July 2017

Recreated in simulation

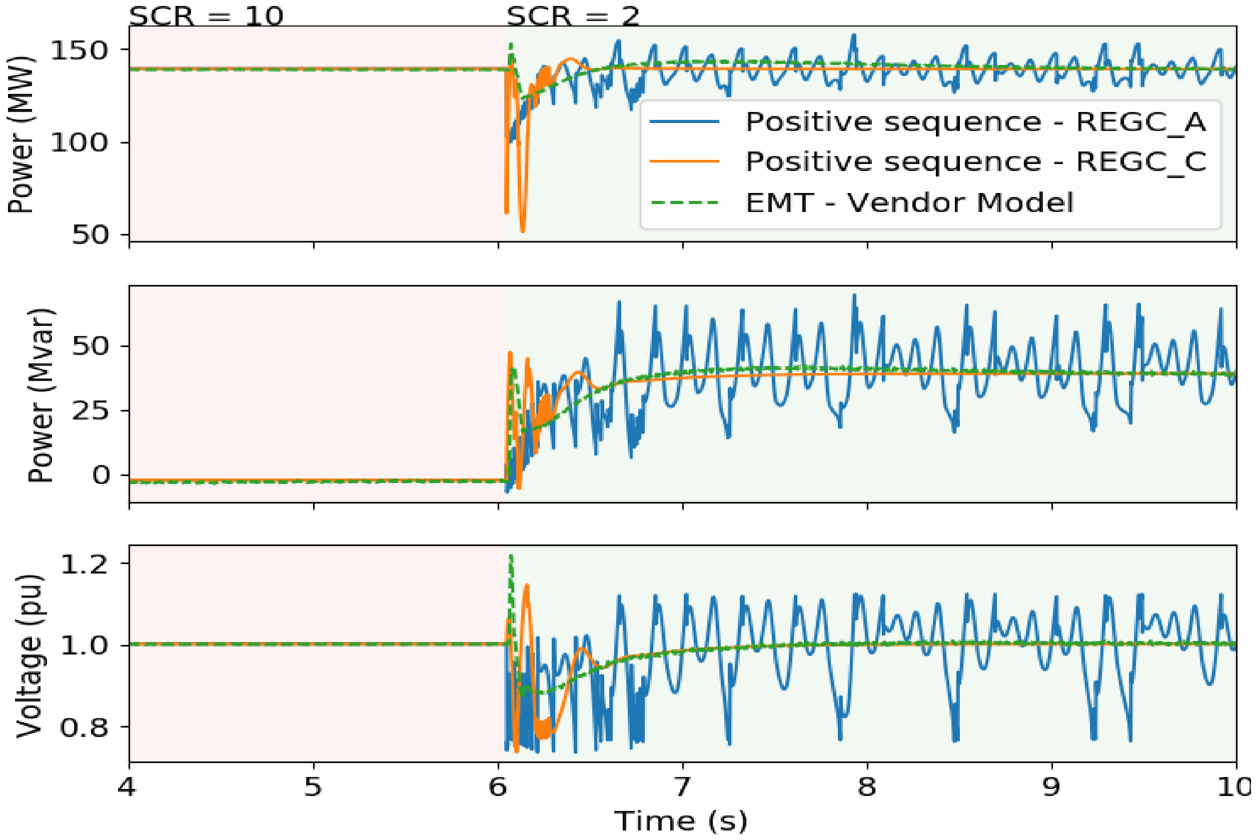


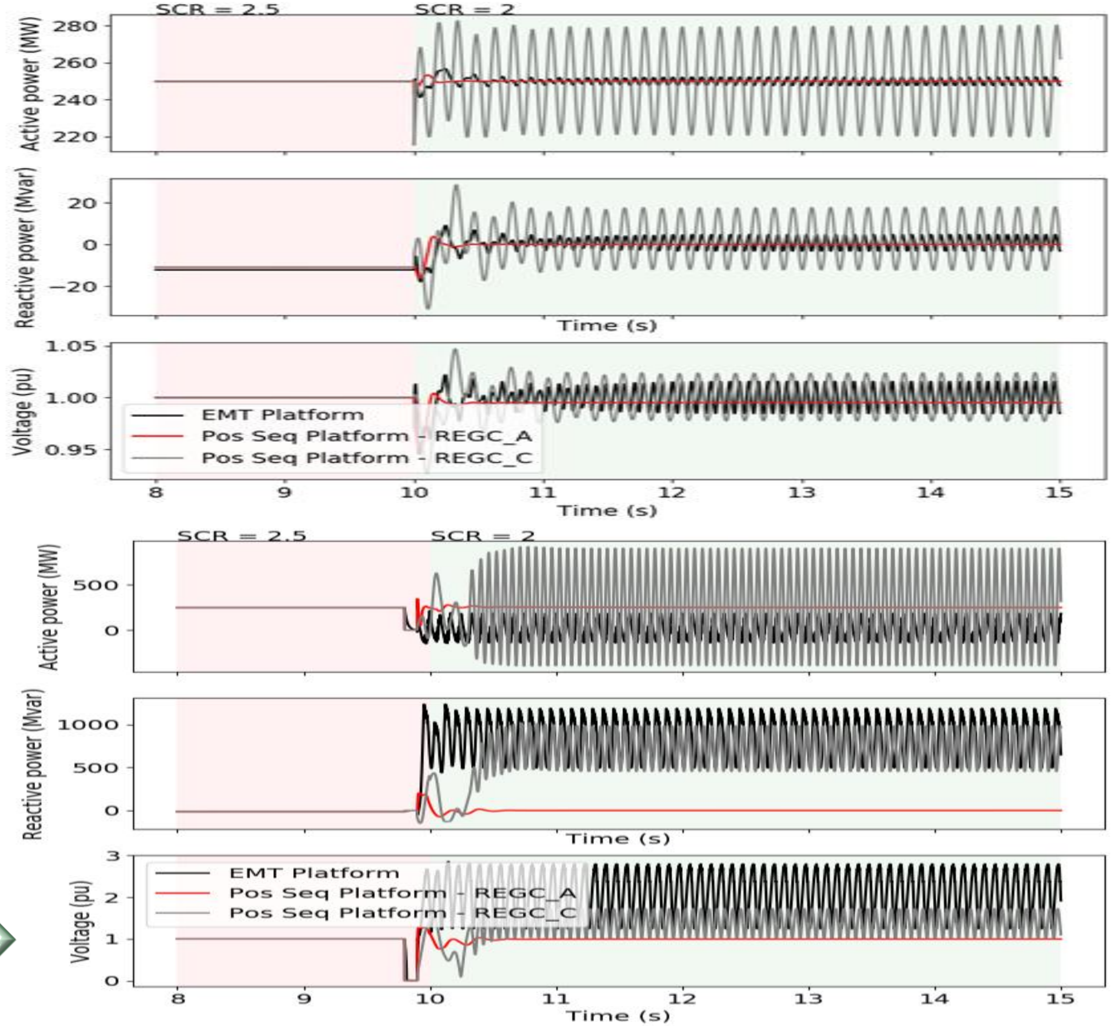
- Use of improved robust positive sequence to re-create low short circuit events
  - ~ 7 Hz oscillation observed in SCADA measurement
  - ~ 9 Hz oscillation observed in simulation
- Simulation time scale is for computation efficiency

Reference: D. Ramasubramanian *et al.*, "Positive sequence voltage source converter mathematical model for use in low short circuit systems," in *IET Generation, Transmission & Distribution*, vol. 14, no. 1, pp. 87-97, 17 1 2020 (link)

Project was in collaboration with PEACE, PLLC. and First Solar

Example 2: Recreation of weak grid oscillatory events using REGC_C model



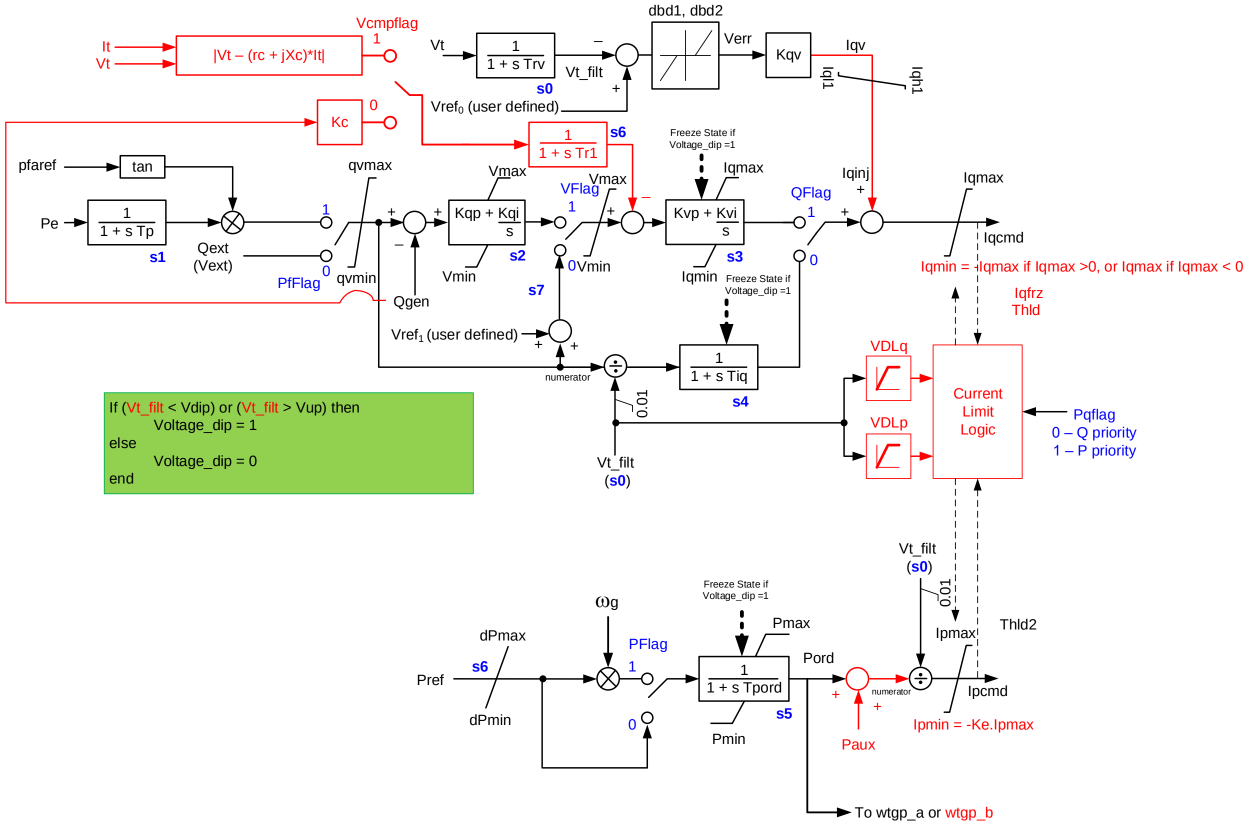


User defined positive sequence model from OEM was unable to show the oscillations

Deepak Ramasubramanian, Xiaoyu Wang, Sachin Goyal, Manjula Dewadasa, Yin Li, Robert J. O'Keefe, and Peter F. Mayer, "Parameterization of Generic Positive Sequence Models to Represent Behavior of Inverter Based Resources in Low Short Circuit Scenarios," *Electric Power Systems Research*, Volume 213, 2022, 108616

REEC_D

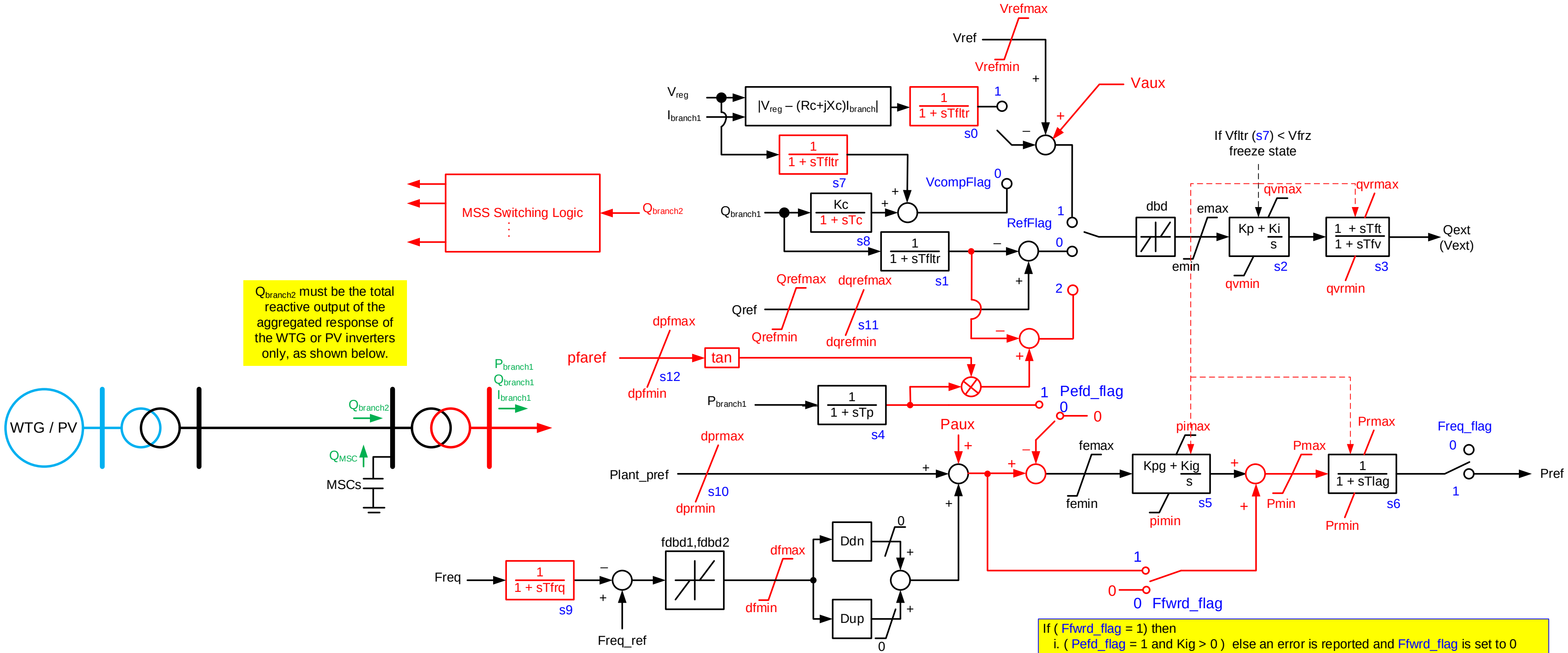
- Input from Senvion, Siemens-Gamesa, GE, FirstSolar and others



Improved VDL Tables + Local Current Comp.

REPC_C

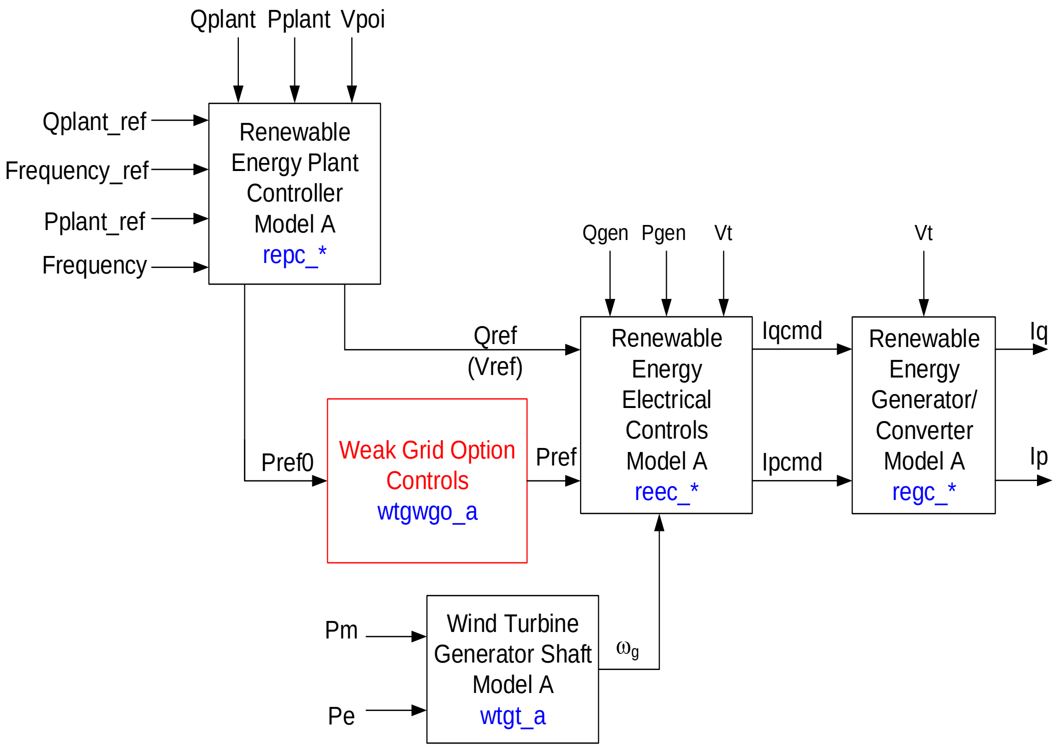
- Input from Senvion, Siemens-Gamesa, GE, FirstSolar and others

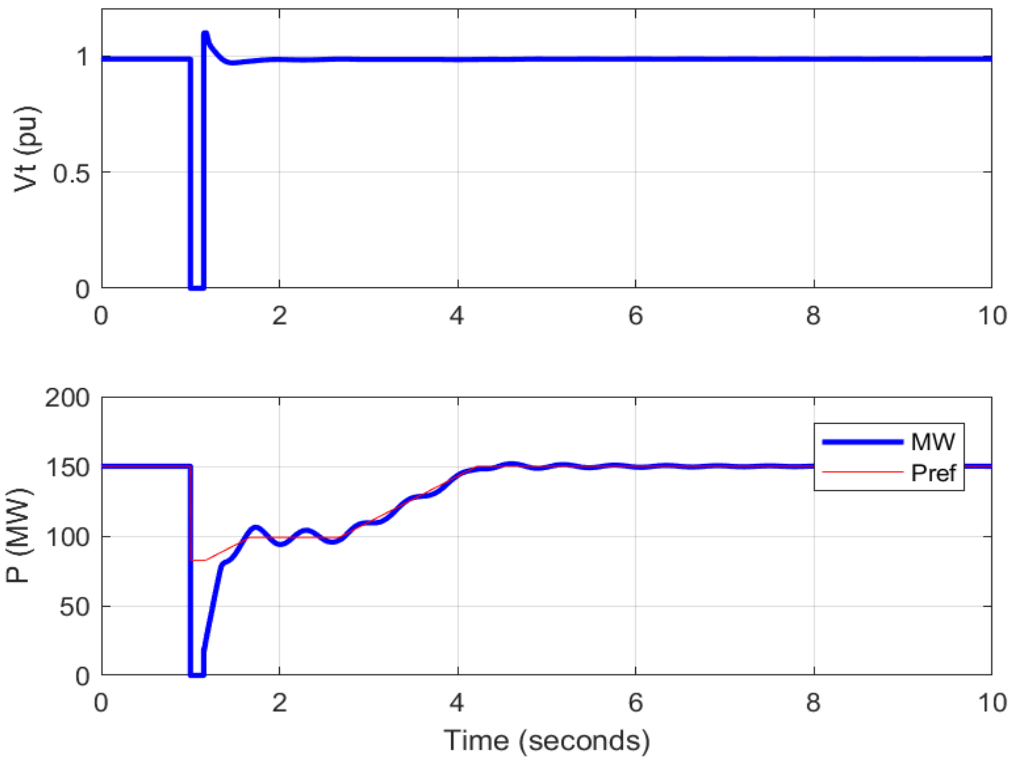


If (Ffwrd_flag = 1) then
i. (Pefd_flag = 1 and Kig > 0) else an error is reported and Ffwrd_flag is set to 0
ii. During initialization Plant_pref = s4 ($P_{branch0}$) and s5 = s6 - s4
iii. In this case the parameters pimax & pimin and Pmax & Pmin are independent
else if (Ffwrd_flag = 0)
i. Pefd_flag and Kig can both be zero or non-zero
ii. Model initializes the normal way, as appropriate
iii. In this case pimax = Pmax and pimin = Pmin (this must be forced internally, giving priority to the values of Pmax/Pmin)
end

Significant Additions to Control Features

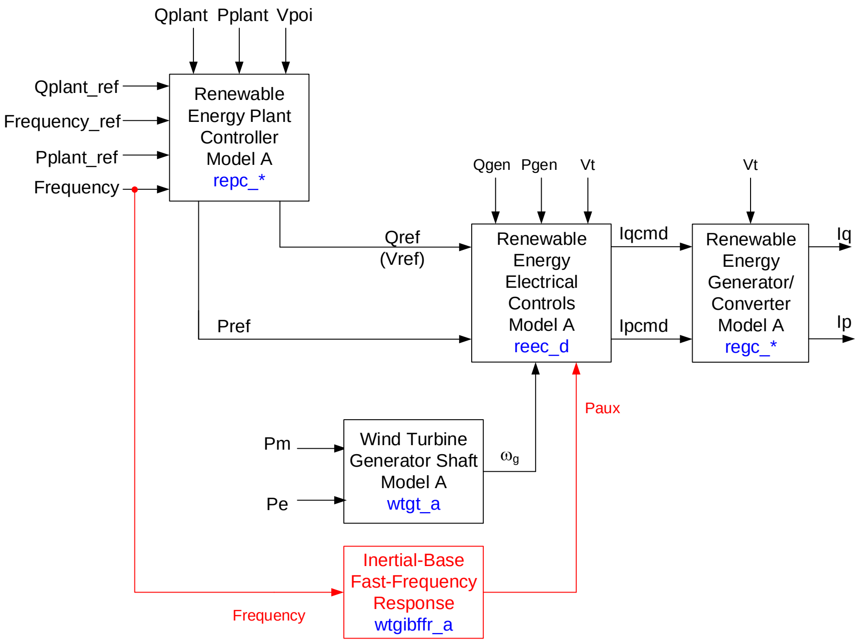
WGO – Weak Grid Option

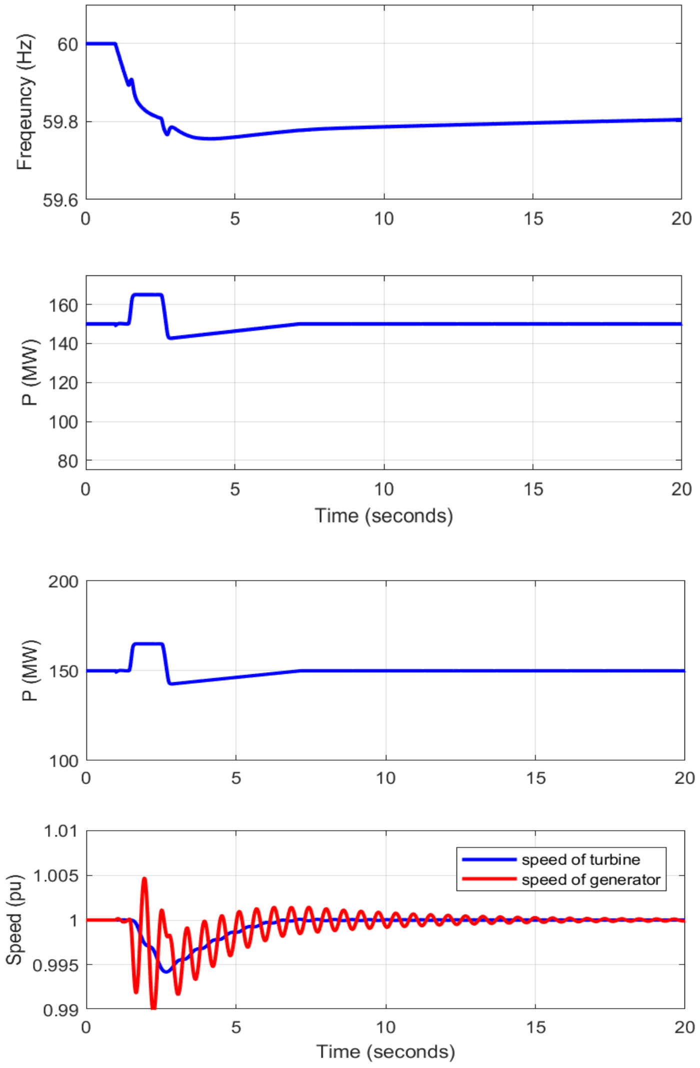


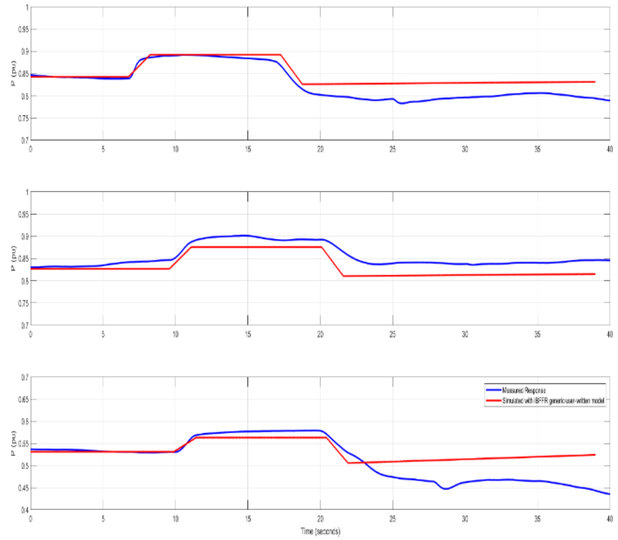


Inertia-Based Fast Frequency Response for WTGs

WTGIBFFR

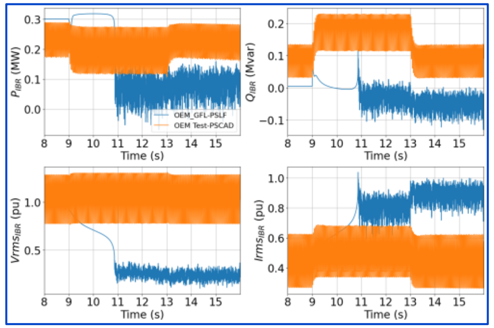




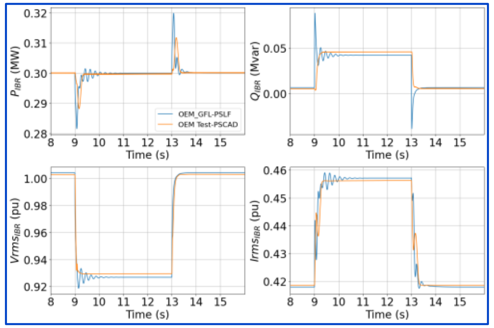


Comparison of performance of OEM EMT model against appropriate positive sequence parameterization

Step change in voltage



SCR = 1.0



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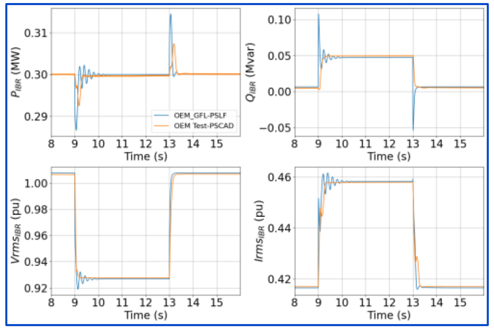

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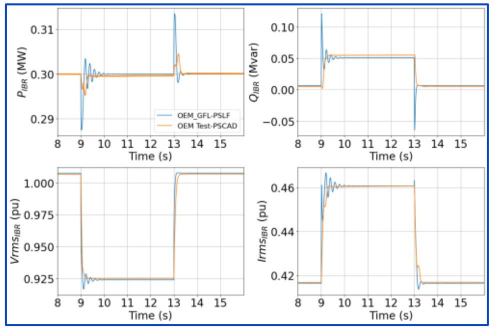
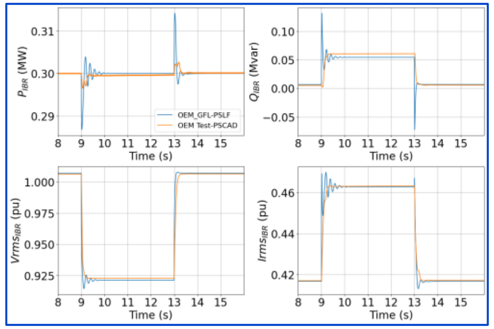
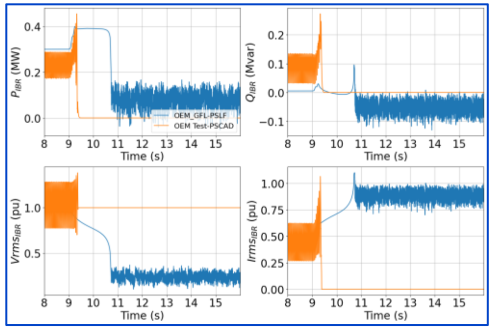


SCR = 4.0



SCR = 5.0

Step change in frequency



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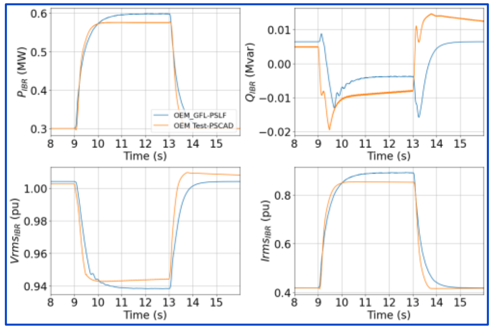

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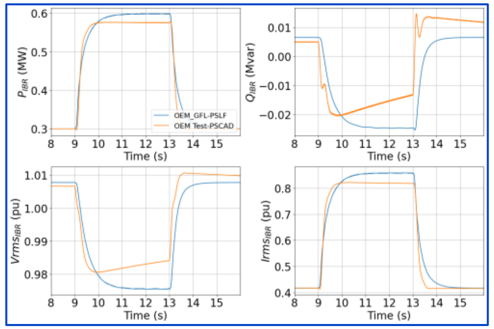
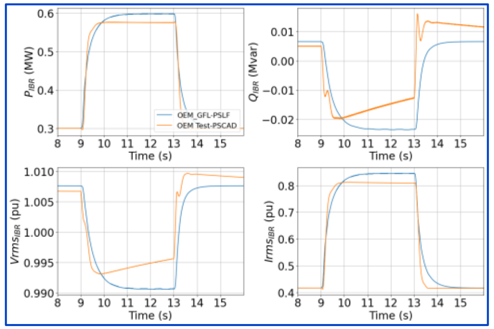
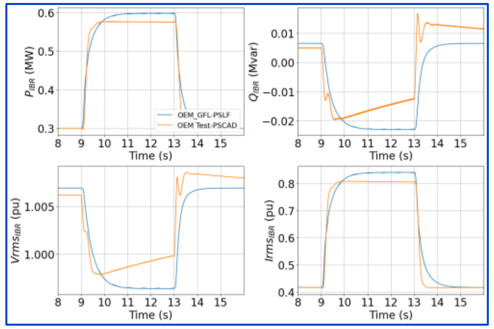


SCR = 3.0



SCR = 4.0



SCR = 5.0

Appropriate parameterization of GFL PSLF model allows for sufficient estimation of performance of today's IBR

REGC_B + REEC_C + REPC_A

Will these new positive sequence models be sufficient?

- EMT studies will continue to remain important with increase in IBRs
- New positive sequence models provide additional insight in carrying out studies and analysis
- They enable further screening of cases for which detailed EMT studies may be required
- They allow for more robust and accurate representation of IBR behavior while carrying out real time operations dynamic analysis

Model limitation versus simulation domain limitation

- Present models in planning base cases (both positive sequence and EMT) have been unable to capture causes of inverter tripping
- Limitation of a model should not be confused with limitation of the simulation domain itself
- Models (such as REGC_C and other future models) can help bring about added capability that can be leveraged

Cause of observed behavior	Simulation domain limitation	Most of today's model incorrectly parameterized	Most of today's model do not represent	
Unbalanced conditions	✓			
Sub-cycle ac over voltage	✓			
Sub-cycle ac over current	✓			
Momentary cessation		✓		Future model can represent as capability exists in simulation domain
Error in frequency measurement		✓		
PLL loss of synchronism		✓		
Collector network level under frequency		✓		
Phase jump			✓	
dc reverse current			✓	
dc low voltage			✓	
Plant controller interactions			✓	

(a) Positive sequence simulation domain

Cause of observed behavior	Simulation domain limitation	Most of today's model incorrectly parameterized	Most of today's model do not represent	
Unbalanced conditions		✓		Future model can represent as capability exists in simulation domain
Sub-cycle ac over voltage		✓		
Sub-cycle ac over current		✓		
Momentary cessation		✓		
Error in frequency measurement		✓		
PLL loss of synchronism		✓		
Collector network level under frequency		✓		
Phase jump			✓	
dc reverse current			✓	
dc low voltage			✓	
Plant controller interactions			✓	

(b) EMT simulation domain

Differentiating between Applicability of Simulation Domains and Inverter Mathematical Models in these Domains. EPRI. Palo Alto, CA: 2022. 3002025063.

Summary

- Large power systems are commonly simulated using positive sequence simulation tools

- In order to conduct future planning studies, availability of adequate simulation models in the library of these software is important.

- Newer positive sequence models have been developed that can improve the state of art of representing IBR behavior
  - Not to be construed as replacement of EMT domain. Rather, meant to complement EMT domain studies

- With IBR newer control methods such as grid forming behavior, state of the art of positive sequence models continue to improve.

- Diligent parameterization of a suitable model is extremely crucial.

Content
(9:00 a.m. – 12:00 p.m.)

9:00 a.m. **Background and Motivation**
John Seuss & Jens Boemer

9:15 a.m. **High-level review of Power Electronics Basics for PV Inverters, IBR Controls, and Applicable IEEE Standards**
Jens Boemer

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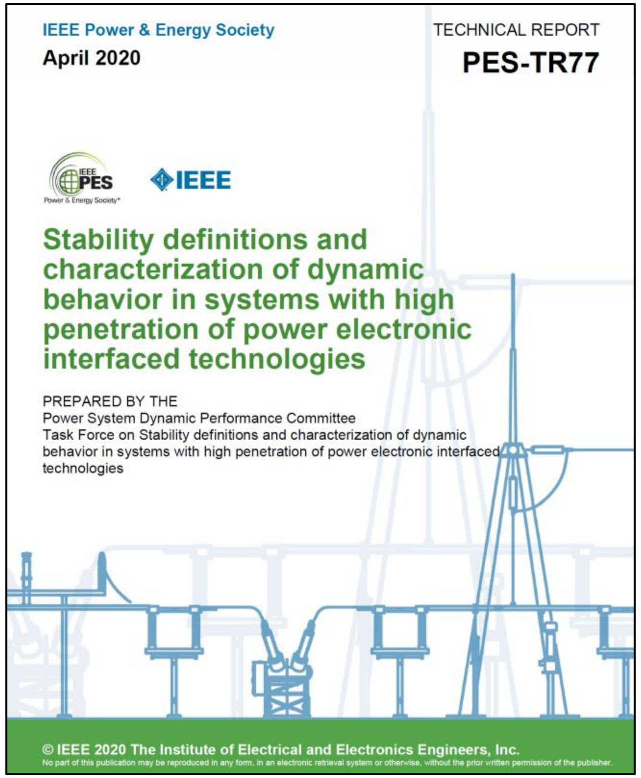
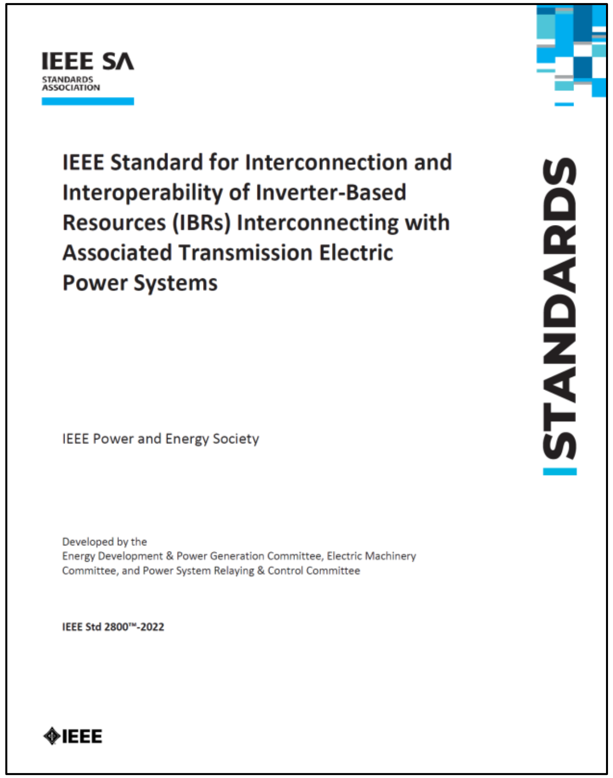
11:45 a.m. **Additional Q&A / Overflow**

EPRI

Need for EMT models of IBRs



"Stability definitions and characterization of dynamic behavior in systems with high penetration of power electronic interfaced technologies," Technical Report April, 2020. [Online]. Available: https://resourcecenter.ieee-pes.org/publications/technical-reports/PES_TP_TR77_PSDP_stability_051320.html



"IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems," in *IEEE Std 2800-2022* , vol., no., pp.1-180, 22 April 2022, doi: 10.1109/IEEESTD.2022.9762253.

https://www.nerc.com/pa/rrm/ea/Pages/Major-Event-Reports.aspx

MOD-026-2 – Verification of Dynamic Models and Data for BES Connected Facilities

A. Introduction

1. **Title:** Verification of Dynamic Models and Data for BES Connected Facilities
2. **Number:** MOD-026-2
3. **Purpose:** To verify that the dynamic models and associated parameters used to assess Bulk Electric System (BES) reliability represent the in-service equipment of BES Facilities including generating Facilities, transmission connected dynamic reactive resources, and high-voltage direct current (HVDC) systems.

https://www.nerc.com/pa/Stand/Pages/Project-2020_06-Verifications-of-Models-and-Data-for-Generators.aspx

Project 2022-04 EMT Modeling

Related Files

Status
The comment and nomination period for the **Project 2022-04 EMT Modeling Standard Authorization Request (SAR)** concluded at **8 p.m. Eastern, Tuesday, September 13, 2022.**

Background
The bulk power system (BPS) in North America is undergoing a rapid transformation towards high penetrations of inverter-based resources. Transmission Planners (TP) and Planning Coordinators (PC) are concerned about the lack of accurate modeling data and the need to perform electromagnetic transient (EMT) studies during the interconnection process and long-term planning horizon. The growth of inverter technology has pushed conventional planning tools to their limits in many ways, and TPs and PCs are now faced with the need to conduct more detailed studies using EMT models for issues related to inverter-based resource integration issues.

This SAR proposes including EMT models and studies in planning-related NERC Standards to ensure reliable operation of the BPS moving forward.

Standard(s) Affected: FAC-002, MOD-032, and TPL-001

Purpose/Industry Need
This project addresses the reliability-related need and benefit by ensuring TPs and PCs have the models and tools necessary to adequately conduct reliability assessments under increasing levels of inverter-based resources. This requires the collection of EMT models by applicable entities and TPs and PCs to conduct EMT studies where needed.

https://www.nerc.com/pa/Stand/Pages/Project2022-04EMTModeling.aspx

Need for Generic Models
Transmission planning perspective

- Futuristic studies
- Development and communication of grid-specific performance requirements
- Investigation of site-specific requirements
- Existing facilities where EMT models are not available
- Education

But … the model should be reasonable

Generic EMT Model for PV and Storage

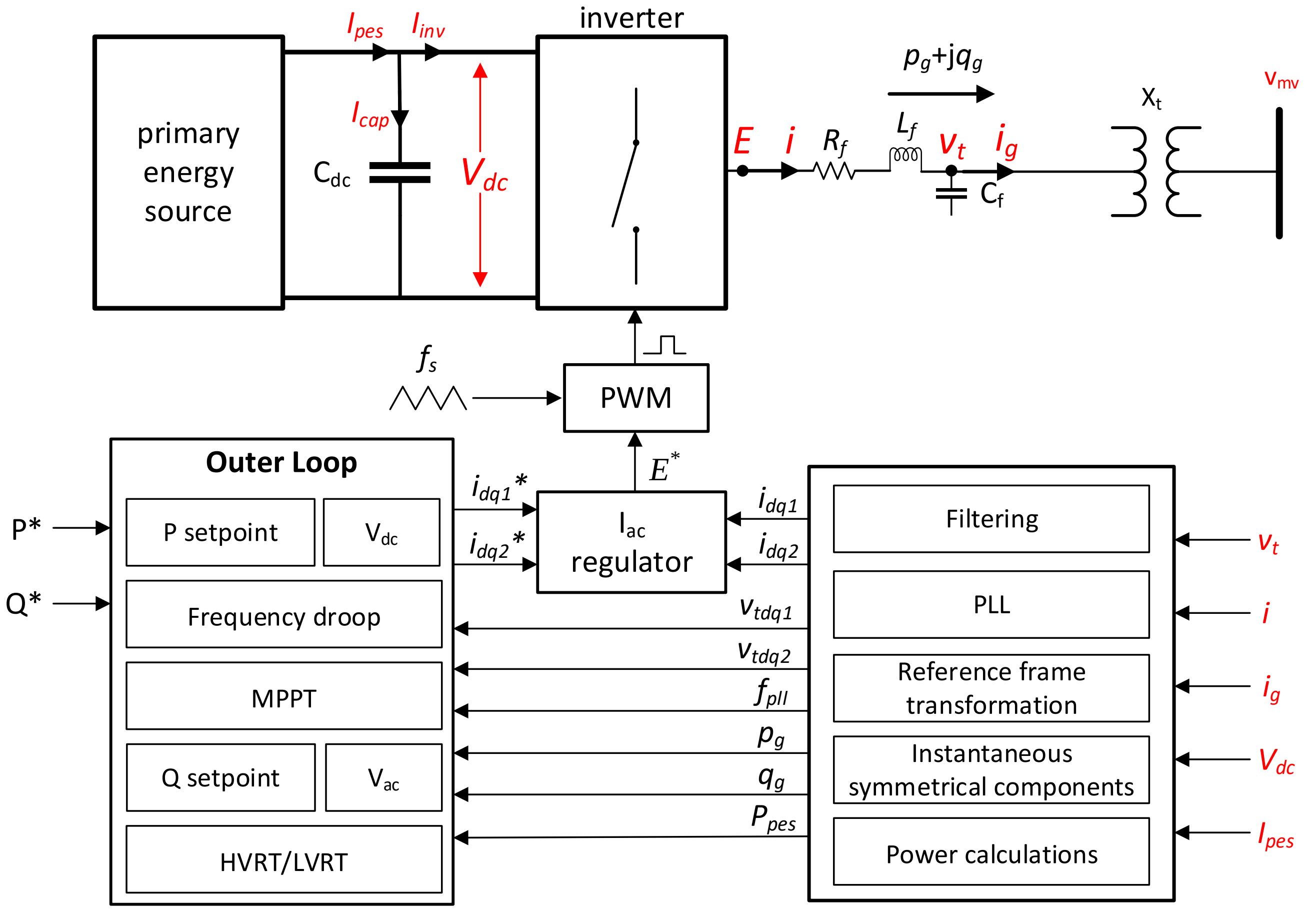
Based on IEEE Std 2800-2022 performance requirements

- Include control that allows the IBR to meet the IEEE Std 2800-2022 performance requirements
- Include varying levels of modeling simplifications
  - DC dynamics
  - Converter model
- Ensure the model is reasonable
  - Comparisons to commercial inverter responses

Ref: Generic Photovoltaic Inverter Model in an Electromagnetic Transients Simulator for Transmission Connected Plants: PV-MOD Milestone 2.7.3. EPRI, Palo Alto, CA: 2022
https://publicdownload.epri.com/PublicAttachmentDownload.svc/AttachmentId=82135

Generic EMT model

PV or storage inverter model

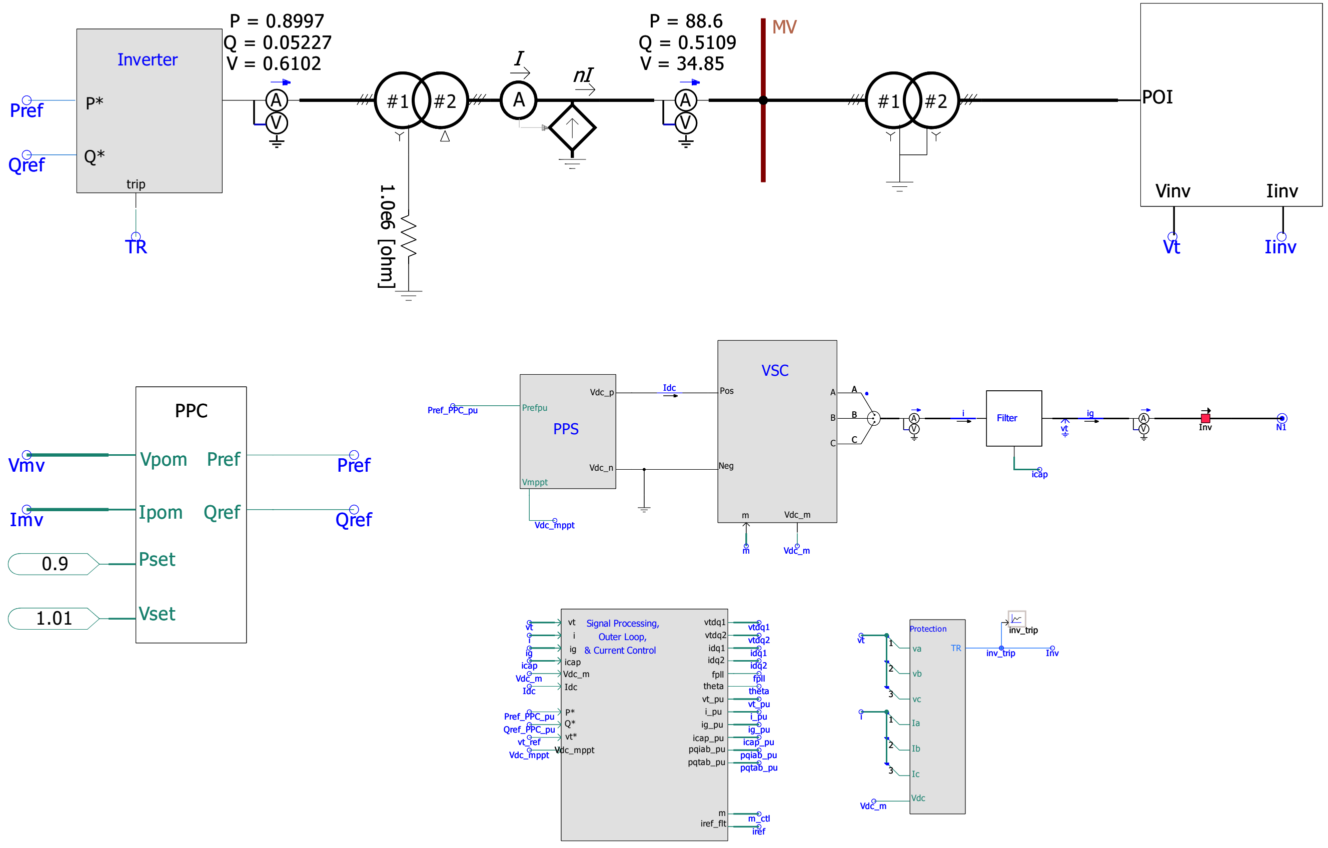


Generic inverter model

- → Current-controlled, PWM VSC
- → Control implemented in dual dq frames: positive and negative sequences
- → Controllers developed based on IEEE 2800-2022 FRT response requirements
- → Setpoint controllers: Vdc, P, Vac, and Q

Ref: Generic Photovoltaic Inverter Model in an Electromagnetic Transients Simulator for Transmission Connected Plants: PV-MOD Milestone 2.7.3. EPRI, Palo Alto, CA: 2022
https://publicdownload.epri.com/PublicAttachmentDownload.svc/AttachmentId=82135

Generic EMT model
Implemented in PSCAD™



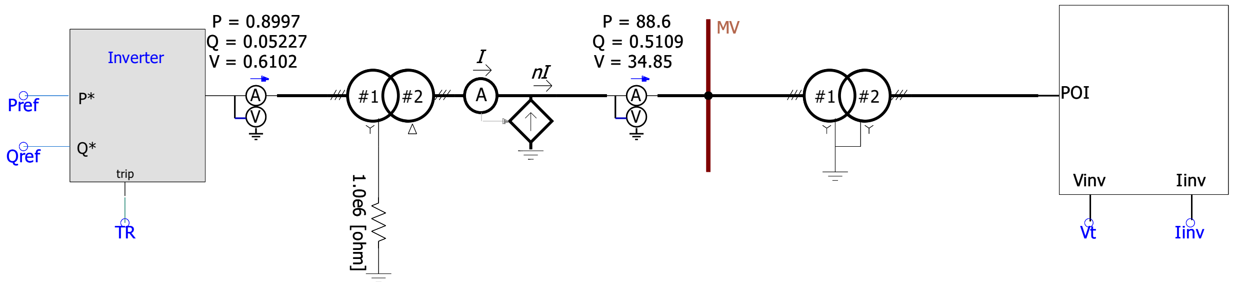
0. inverter data	
Sinv: Inverter rated aparant power (VA)	1e6
VLL_base: inverter rated RMS voltage line-line (V)	600
fnom: nominal frequency	60.0
Lf: LC filter inductance	0.0001
Rf: LC filter resistance	0.00075
Cf: LC filter capacitance (uF)	147
Rd: LC filter damping resistance	0.05 [ohms]
Cdc: DC link capacitor capacitance (uF)	0.1e6
Vdc_nom: DC link voltage nominal	1200
fs: PWM switching frequency (switching model)	3060.0
tstart_up: Start-up time	2.0
1. control configuration	
Vsp_flg (1: enable inverter term. voltage control, (	0
Qsp_CL_flg (1: closed loop Q control, 0: open loo|	0
qt_flg (1: Q control at terminal after LC filter, 0: Q	1
Vdc_flg (1: enable Vdc control, 0: voltage source (	0
PV_flg (1: enable PV array I-V characteristic, 0: co	0
MPPT_flg (1: enable MPPT for Vdc*, requires VI-fl	0
f_flg (1: to enable frequency-droop control, 0: dis:	0
2. reactive power - voltage control	
Qmax: reactive power maximum limit	0.4
Qmin: reactive power minimum limit	-0.4
iq1_max: reactive current maximum limit	99
iq1_min: reactive current minimum limit	-99
Kqp: Q closed-loop propotional gain	0
Kqi: Q closed-loop integral gain	40
Kvp: terminal voltage control proportional gain	0
Kvi: terminal voltage control integral gain	100
vt_ref: terminal voltage control reference setpoint	1.0
Tv: Voltage LPF time constant	0.01
3. Vdc control	
kp_vdc: Vdc propotional gain	5.18
ki_vdc: Vdc integral gain	52.91
4. frequency-droop	
fdbd1: deadband for frequency droop control (< (	-0.0006
fdbd2: deadband for frequency droop control (> (	0.0006
Dup: 1/Droop for low frequency	20.0
Ddn: 1/Droop for high frequency	20.0
Tfrq: 1st order LPF time constant for PLL frequenc	0.1

5. FRT	
Ilim_pu: current limit	1.0
ipri_flg: current priority (1: iq, 0: ip)	1
Vlvrt: threshold for LVRT	0.9
Vhvrt: threshold for HVRT	1.1
V1_frt_dbstep_flg: set FRT V1 deadband as step	0
Kqv1_lvrt: LVRT V1 proportional gain	2
Kqv1_hvrt: HVRT V1 proportional gain	2
iq1i_flg	1
Kqv 2: FRT V2 proportional gain	2
V2_db: V2 FRT dead band	0.1
V2_frt_dbstep_flg: set FRT V1 deadband as step	1
DelI_flg	1
6. PLL	
kp_pll: Propotional gain for PLL	40
ki_pll: Integral gain for PLL	4
limpllmax: PLL integrator windup limit	70
7. signal processing	
Iflt_flg: Current filter flag (1: enable)	1
Tflt_i: Current LPF time constant	0.00001
Vflt_flg: Voltage filter flag (1: enable)	1
Tflt_v: Voltage LPF time constant	0.00001
8. current control	
kp_cur: Proportional gain current controller	0.9
ki_cur: Integral gain current controller	900.0
limcurmax: anti-windup upper limit	99999
limcurmin: anti-windup lower limit	-99999
ip_ramp_up: Ramp rate for increasing active curre	1.0
Vff_flg: (1: enable voltage feedforward, 0: disable	0
Tvff: Vff LPF time constant	0.0001

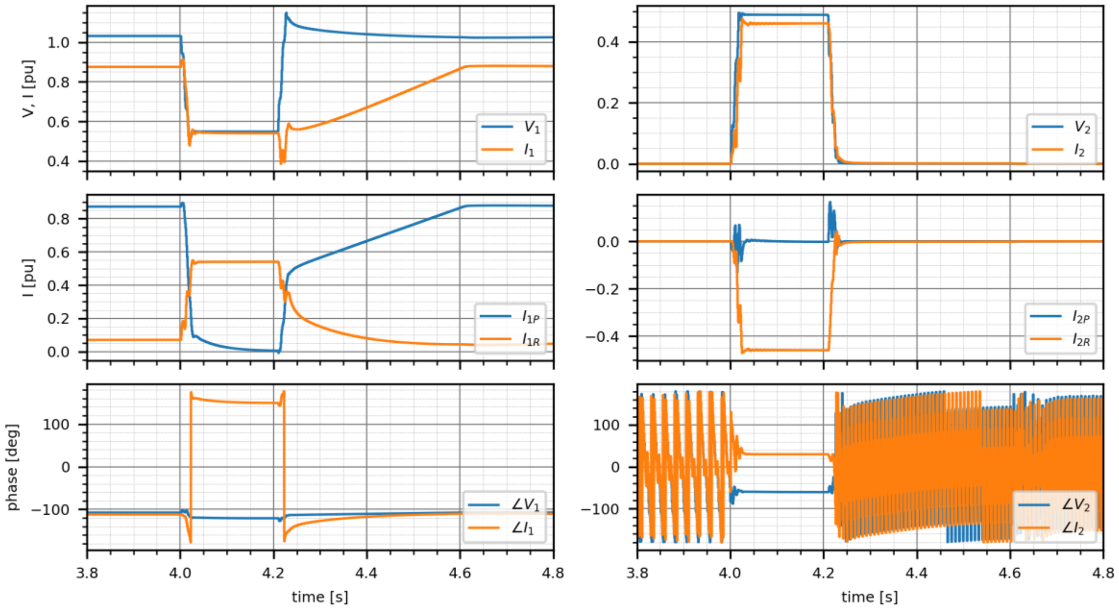
Ref: PRE-SW: Generic Photovoltaic Inverter Model in an Electromagnetic Transients Simulator for Transmission Connected Plants (PVMOD-EMT-IBR) v1.0 Beta. EPRI, Palo Alto, CA: 2023. 3002025889 Online: https://www.epri.com/research/products/000000003002025889

Generic EMT model

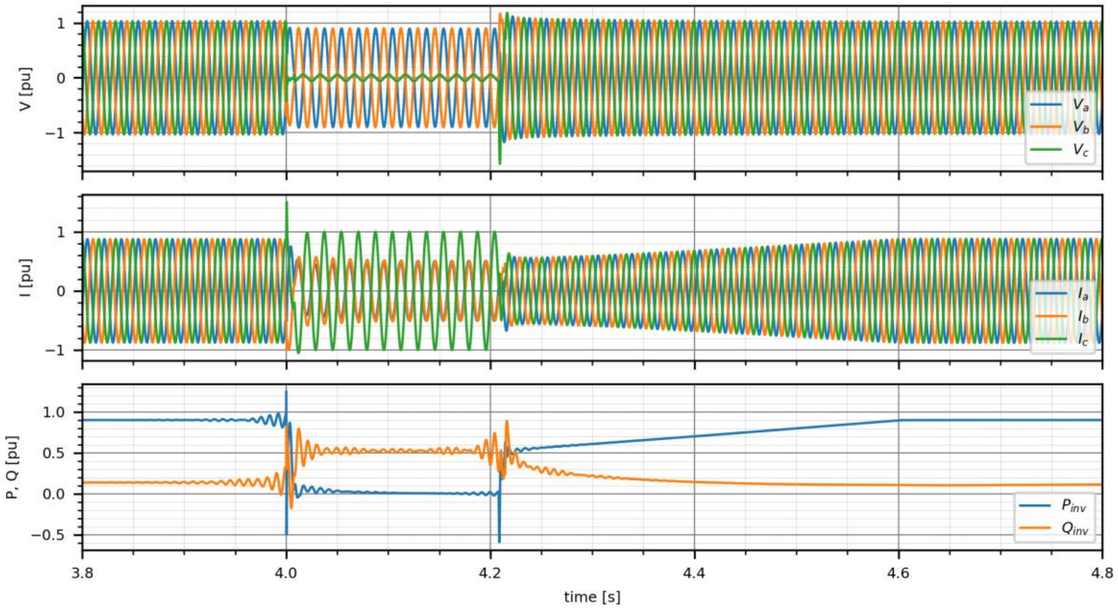
FRT response tests: B-C fault at POI example



B-C fault: Fundamental Freq. Symmetrical Components



Instantaneous voltage, current, active power, and reactive power

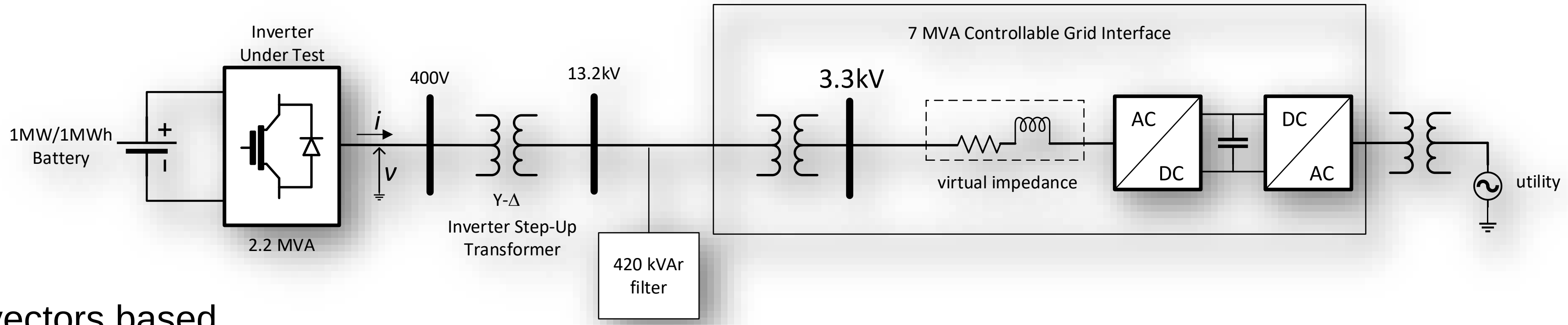


Ref: W. Baker, M. Patel, A. Haddadi, E. Farantatos, J. Boemer, “Inverter Current Limit Logic based on the IEEE 2800-2022 Unbalanced Fault Response Requirements”, *2023 IEEE Power Engineering Society General Meeting*

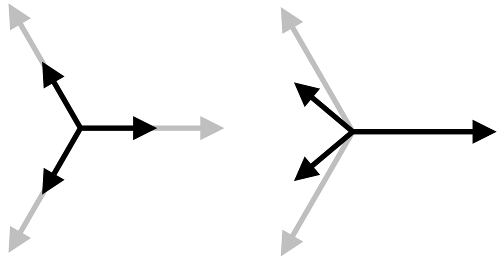
Validation example

Laboratory testing of a 2.2 MVA commercial battery inverter

Laboratory test circuit



Voltage vectors based on IEEE Std 1668-2017



LLLG LL

Varying residual voltage in faulted phases at the 13.2 kV bus

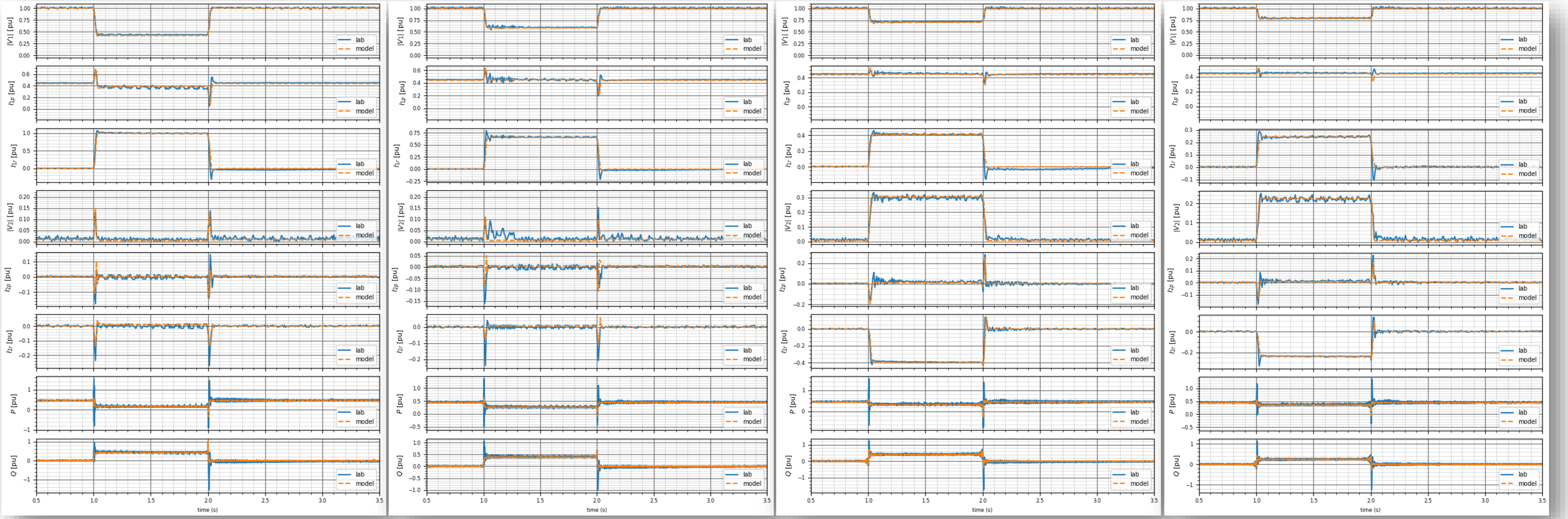
Fault type	Faulted Phase(s) Residual 13.2 kV Voltage [pu]
LLLG	0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9
LL (B-C)	0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9

1. NREL test facility: https://www.nrel.gov/docs/fy19osti/72886.pdf
2. Draft Test Plan and Candidate Inverter List: Adaptive Protection and Validated MODels to Enable Deployment of High Penetrations of Solar PV (PV-MOD). EPRI, Palo Alto, CA: 2023. Milestones 1.3.2 and 1.3.3 report for DOE. Online: https://publicdownload.epri.com/PublicAttachmentDownload.svc/AttachmentId=82091 and https://www.epri.com/pvmod
3. W. Baker, D. Ramasubramanian, A. Huque, J. Boemer, V. Gevorgian, P. Koralewicz, E. Mendiola, "Validation of the Fault Ride-Through Response of a Generic EMT Inverter Model by Laboratory Testing", *2023 IEEE Power Engineering Society General Meeting*

Model response comparison

Comparison of the EMT model's response ('model') to the measured response of the IUT ('lab') to balanced and unbalanced faults

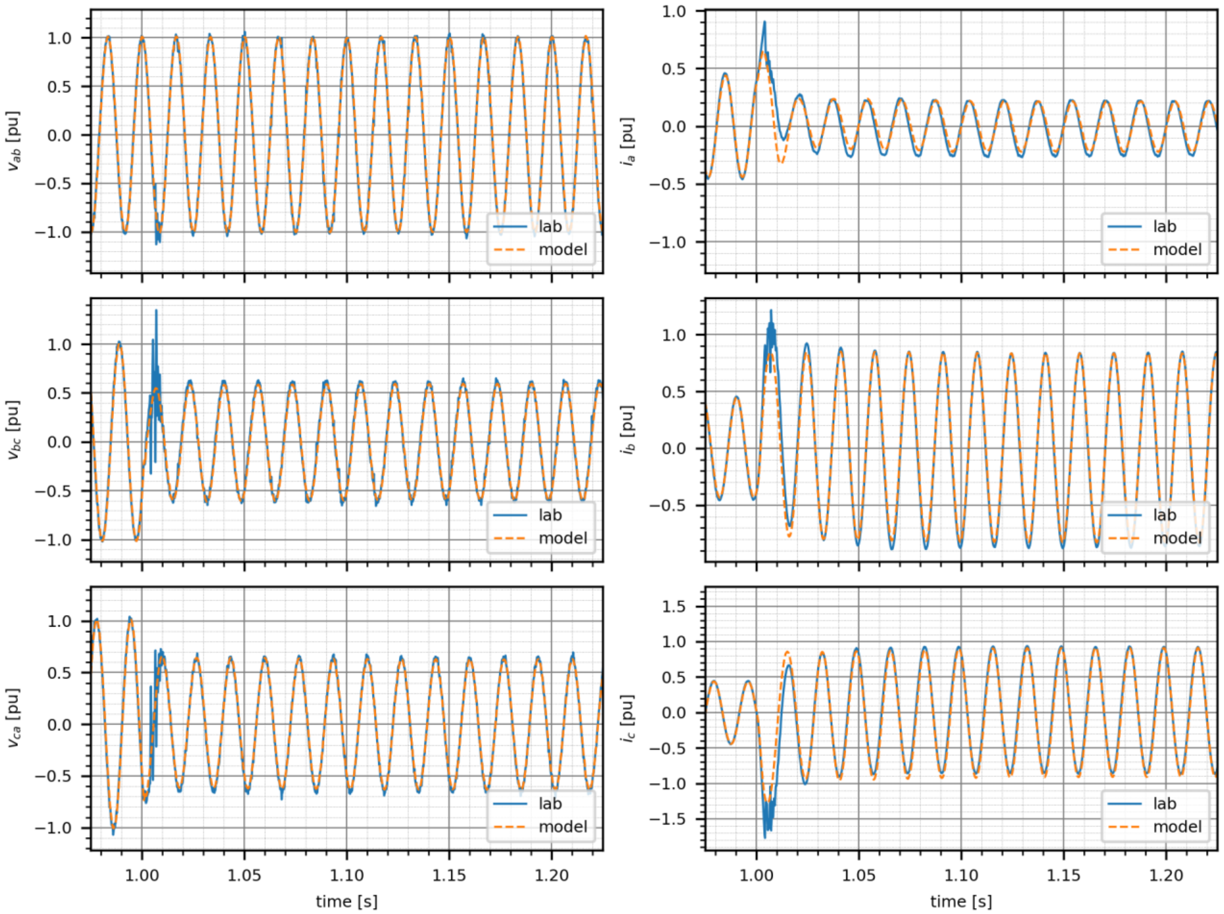
LLLG fault with $|\mathbf{V_1}|$=0.4 pu | LLLG fault with $|\mathbf{V_1}|$=0.6 pu | B-C fault with $|\mathbf{V_2}|$=0.3 pu | B-C fault with $|\mathbf{V_2}|$=0.22 pu



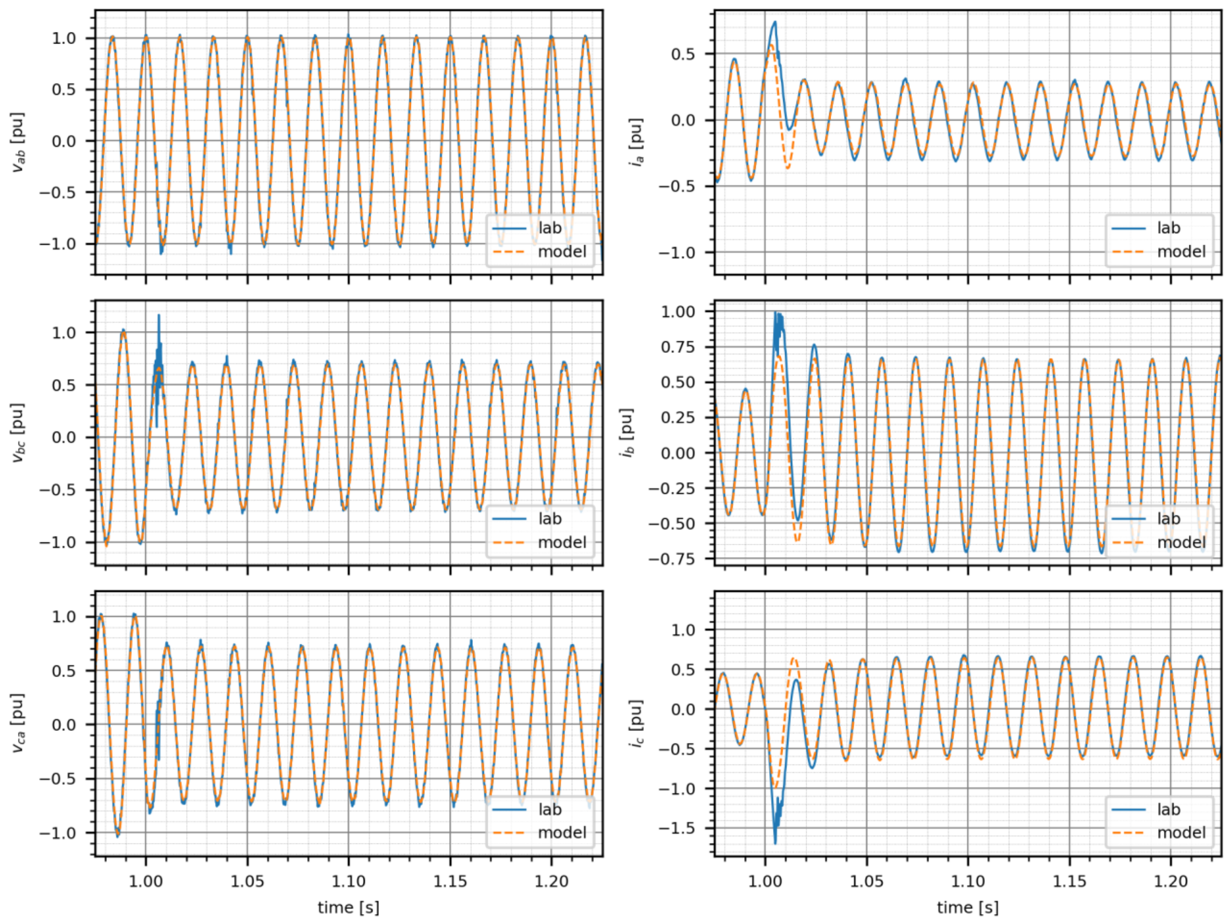
Ref: W. Baker, D. Ramasubramanian, A. Huque, J. Boemer, V. Gevorgian, P. Koralewicz, E. Mendiola, "Validation of the Fault Ride-Through Response of a Generic EMT Inverter Model by Laboratory Testing", *2023 IEEE Power Engineering Society General Meeting*

Model response comparison

Instantaneous line-line voltage and current at fault inception



B-C fault 30% retained voltage



B-C fault 50% retained voltage

Ref: W. Baker, D. Ramasubramanian, A. Huque, J. Boemer, V. Gevorgian, P. Koralewicz, E. Mendiola, “Validation of the Fault Ride-Through Response of a Generic EMT Inverter Model by Laboratory Testing”, *2023 IEEE Power Engineering Society General Meeting*

Summary
Model response comparison

- The generic EMT inverter model provides a reasonable prediction of the commercial inverter's FRT response for various fault types, fault severity, and initial operating conditions.

- Differences in the transient periods are observed as expected.
  - Details of the commercial inverter's design and control are unknown.
  - All details of the test circuit are not known.

- Expectation is that inverter models developed by the inverter OEMs should be much more accurate.

Content
(9:00 a.m. – 12:00 p.m.)

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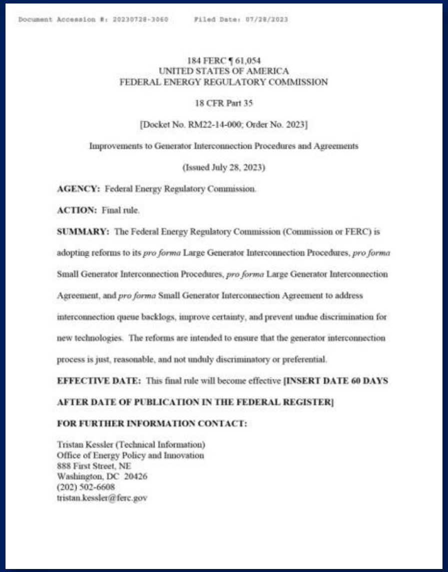
Jens Boemer

11:40 a.m. **High-level review of DER Modeling for Transmission Planning Studies**
Jens Boemer

11:45 a.m. **Additional Q&A / Overflow**

FERC Order 2023 Improvements to Generator Interconnection Procedures and Agreements (RM22-14)

- Administrative reforms:
  - Implement a **first-ready, first-served** study process
  - Improve interconnection queue **processing speed**
- Flexibility
  - Increase flexibility and **incorporate technological advancements** into the interconnection process
- Modeling requirements
  - A **validated user-defined RMS** positive seq. dynamics model
  - An **appropriately parameterized, generic library RMS** positive sequence dynamics model
  - A **validated EMT model**, only if the transmission provider performs an EMT study in interconnection process
- Performance requirements
  - Establish **ride through requirements** for all resources within the “no trip zone” defined by the NERC PRC-024-3
  - **Declined to incorporate IEEE 2800-2022** by reference and to include plant conformity assessment into interc. process.



Document Accession #: 20230728-3060 Filed Date: 07/28/2023

184 FERC ¶ 61,054
UNITED STATES OF AMERICA
FEDERAL ENERGY REGULATORY COMMISSION

18 CFR Part 35

[Docket No. RM22-14-000; Order No. 2023]

Improvements to Generator Interconnection Procedures and Agreements

(Issued July 28, 2023)

AGENCY: Federal Energy Regulatory Commission.

ACTION: Final rule.

SUMMARY: The Federal Energy Regulatory Commission (Commission or FERC) is adopting reforms to its *pro forma* Large Generator Interconnection Procedures, *pro forma* Small Generator Interconnection Procedures, *pro forma* Large Generator Interconnection Agreement, and *pro forma* Small Generator Interconnection Agreement to address interconnection queue backlogs, improve certainty, and prevent undue discrimination for new technologies. The reforms are intended to ensure that the generator interconnection process is just, reasonable, and not unduly discriminatory or preferential.

EFFECTIVE DATE: This final rule will become effective **[INSERT DATE 60 DAYS AFTER DATE OF PUBLICATION IN THE FEDERAL REGISTER]**

FOR FURTHER INFORMATION CONTACT:

Tristan Kessler (Technical Information)
Office of Energy Policy and Innovation
888 First Street, NE
Washington, DC 20426
(202) 502-6608
tristan.kessler@ferc.gov

https://www.ferc.gov/media/e-1-order-2023-rm22-14-000

2023

November 5, 2023

Ruling published in federal register (Order 2023) on September 6, 2023. Effective on November 5, 2023

2024

February 3, 2024

90-day period for transmission providers to submit compliance filing to adopt revisions to the LGIP, LGIA, SGIP, and SGIA

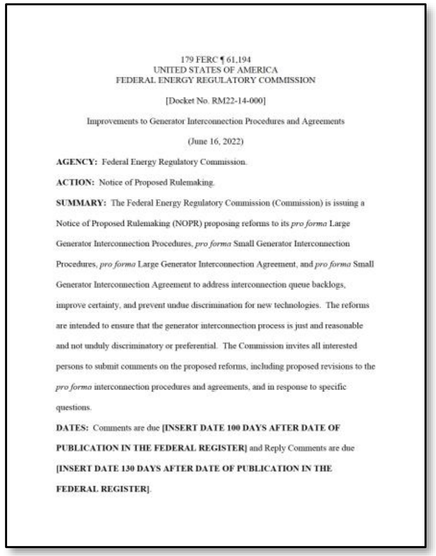
2025+

Ongoing

Possible adoption of voluntary industry standards (e.g., IEEE 2800/.2, IEEE 1547/.1) by Transmission Providers and revision of NERC Reliability Standards

EPRI's Comments to FERC NOPRs

Generator Interconnection (RM22-14)


179 FERC ¶ 61,194
UNITED STATES OF AMERICA
FEDERAL ENERGY REGULATORY COMMISSION

[Docket No. RM22-14-000]

Improvements to Generator Interconnection Procedures and Agreements

(June 16, 2022)

AGENCY: Federal Energy Regulatory Commission.

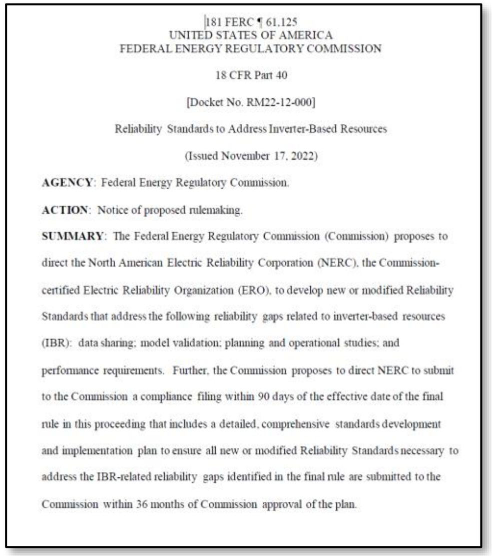
ACTION: Notice of Proposed Rulemaking.

SUMMARY: The Federal Energy Regulatory Commission (Commission) is issuing a Notice of Proposed Rulemaking (NOPR) proposing reforms to its *pro forma* Large Generator Interconnection Procedures, *pro forma* Small Generator Interconnection Procedures, *pro forma* Large Generator Interconnection Agreement, and *pro forma* Small Generator Interconnection Agreement to address interconnection queue backlogs, improve certainty, and prevent undue discrimination for new technologies. The reforms are intended to ensure that the generator interconnection process is just and reasonable and not unduly discriminatory or preferential. The Commission invites all interested persons to submit comments on the proposed reforms, including proposed revisions to the *pro forma* interconnection procedures and agreements, and in response to specific questions.

DATES: Comments are due [INSERT DATE 100 DAYS AFTER DATE OF PUBLICATION IN THE FEDERAL REGISTER] and Reply Comments are due [INSERT DATE 130 DAYS AFTER DATE OF PUBLICATION IN THE FEDERAL REGISTER].

- *Improvements to Large and Small Generator Interconnection Procedures and Agreements:* ***EPRI Comments on FERC's NO****PR issued on June 16, 2022, Docket No. RM22-14-000.* EPRI, Palo Alto, CA: 2022. 3002025703.
- **EPRI Informational Webinar** on FERC Order 2023 on Generator Inter-connection (Transmission), Sep 6, 2023. Recording and Slide Deck.

IBRs Reliability Standards (RM22-12)


181 FERC ¶ 61,125
UNITED STATES OF AMERICA
FEDERAL ENERGY REGULATORY COMMISSION

18 CFR Part 40

[Docket No. RM22-12-000]

Reliability Standards to Address Inverter-Based Resources

(Issued November 17, 2022)

AGENCY: Federal Energy Regulatory Commission.

ACTION: Notice of proposed rulemaking.

SUMMARY: The Federal Energy Regulatory Commission (Commission) proposes to direct the North American Electric Reliability Corporation (NERC), the Commission-certified Electric Reliability Organization (ERO), to develop new or modified Reliability Standards that address the following reliability gaps related to inverter-based resources (IBR): data sharing; model validation; planning and operational studies; and performance requirements. Further, the Commission proposes to direct NERC to submit to the Commission a compliance filing within 90 days of the effective date of the final rule in this proceeding that includes a detailed, comprehensive standards development and implementation plan to ensure all new or modified Reliability Standards necessary to address the IBR-related reliability gaps identified in the final rule are submitted to the Commission within 36 months of Commission approval of the plan.

- *Development of NERC Reliability Standards for IBRs Covering Data Sharing, Model Validation, Planning and Operational Studies, and Performance Requirements:* ***EPRI Comments on FERC's NOPR*** *Issued on November 17, 2022, Docket No. RM22-12-000*. EPRI, Palo Alto, CA: 2023. 3002027507.

EPRI Recommendations:

- consideration of **adoption of IEEE Standards like 2800-2022** to set clear expectations for IBRs' technical minimum capabilities.
  - would have included **comprehensive** and holistic **ride-through capability and performance requirements** instead of explicitly mentioning causes of trips (i.e., loss of PLL synchronism) or causes of slow recovery (i.e., slow ramp rate)
  - was supported—to a different extent—by 7 other entities, including NERC, CAISO, SPP, ACP, SEIA, AEU, NYSRC, AEP, PUCO.
- mandatory submission and **collection of EMT models** in all cases; **all models** should be **validated** and **appropriately parameterized**;
- consideration of modeling as a method for **pre-commissioning conformity assessment**.

Status Quo

Recent Changes in Interconnection Procedure per FERC Large Generator Interconnection Process (LGIP)

Existing Step 1 – Interconnection Request – Plant-Specific Interconnection Request
→ **Existing Step 2** – Feasibility Study – Plant-Specific Interconnection Screening / Preliminary Review
→ **Existing Step 3** – System Impact Study (SIS) – Plant-Specific Grid Integration & Reliability Impact
→ **Existing Step 4** – Facility Study – IBR Plant Cost Estimation and Determination of Transmission Grid Upgrades
→ **IBR Plant Construction** – Installation and Building of All Equipment and Structures
→ **Existing Step 5** – Interconnection Commissioning – Plant-Specific Commissioning & Model Validation/ Verification

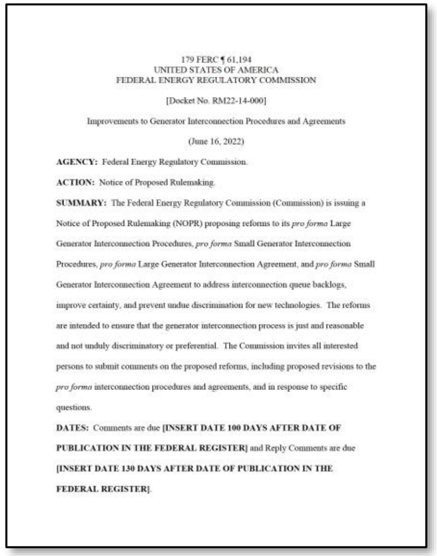
FERC Order 2023

New General Requirement for ISOs/RTOs
Public Interconnection Information
Hosting Capacity Maps ("heat maps")

first-ready, first-served

Existing Step 1 – Interconnection Request – Plant-Specific Interconnection Request
→ FERC did away with the Feasibility Study
→ **Revised Step 3** – Cluster Study – Grid Integration & Reliability Impact Study for all Specific Plants within a Cluster
→ **Revised Step 4** – Facility Study – IBR Plant Cost Estimation and Determination of Transmission Grid Upgrades*
→ **IBR Plant Construction** – Installation and Building of All Equipment and Structures
→ **Existing Step 5** – Interconnection Commissioning – Plant-Specific Commissioning & Model Validation/ Verification

*and Evaluation of Alternative Transmission Technologies


179 FERC ¶ 61,194
UNITED STATES OF AMERICA
FEDERAL ENERGY REGULATORY COMMISSION

[Docket No. RM22-14-000]

Improvements to Generator Interconnection Procedures and Agreements

(June 16, 2022)

AGENCY: Federal Energy Regulatory Commission.

ACTION: Notice of Proposed Rulemaking.

SUMMARY: The Federal Energy Regulatory Commission (Commission) is issuing a Notice of Proposed Rulemaking (NOPR) proposing reforms to its *pro forma* Large Generator Interconnection Procedures, *pro forma* Small Generator Interconnection Procedures, *pro forma* Large Generator Interconnection Agreement, and *pro forma* Small Generator Interconnection Agreement to address interconnection queue backlogs, improve certainty, and prevent undue discrimination for new technologies. The reforms are intended to ensure that the generator interconnection process is just and reasonable and not unduly discriminatory or preferential. The Commission invites all interested persons to submit comments on the proposed reforms, including proposed revisions to the *pro forma* interconnection procedures and agreements, and in response to specific questions.

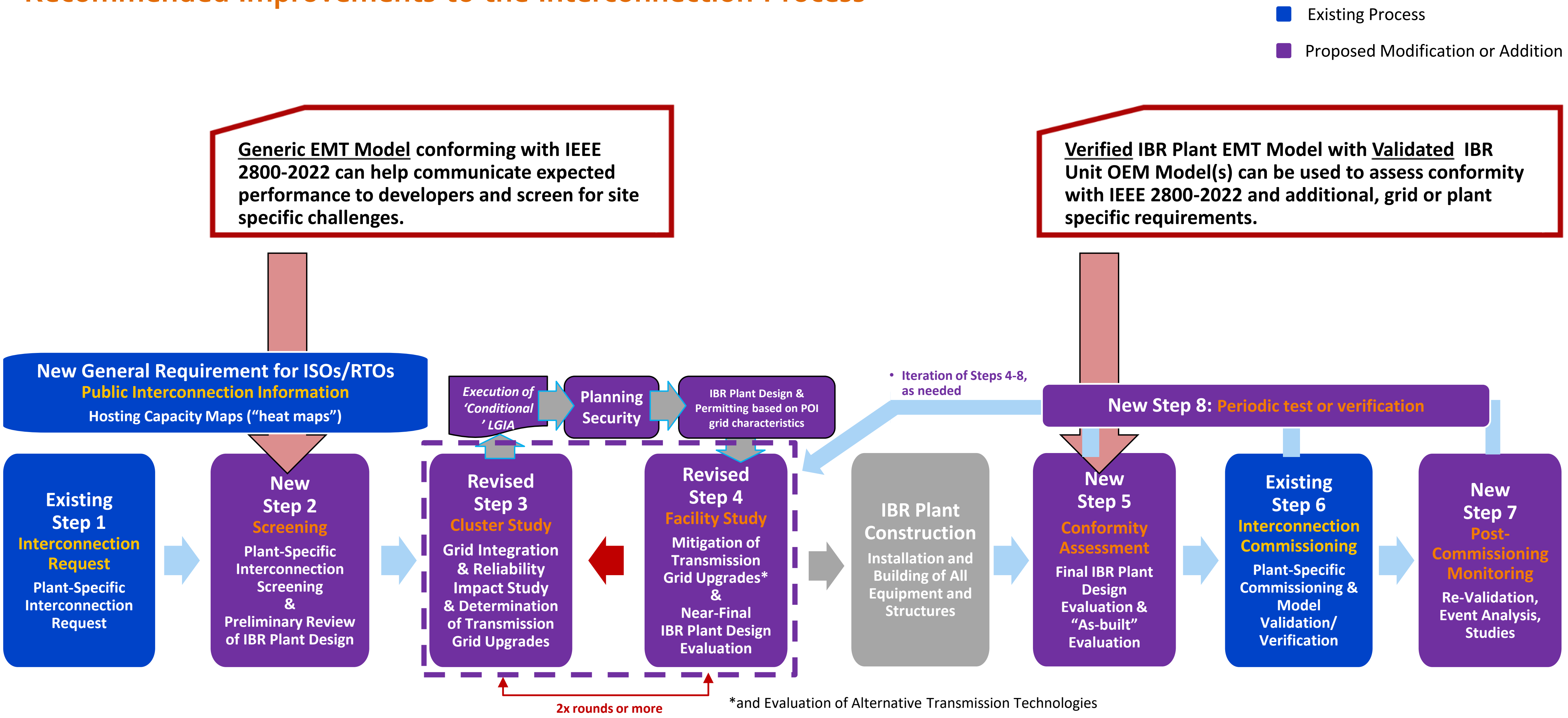
DATES: Comments are due **[INSERT DATE 100 DAYS AFTER DATE OF PUBLICATION IN THE FEDERAL REGISTER]** and Reply Comments are due **[INSERT DATE 130 DAYS AFTER DATE OF PUBLICATION IN THE FEDERAL REGISTER]**.

FERC changed the interconnection process with Order 2023 on July 28, 2023*

**Subject to pending litigation*

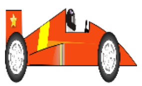
Another Possible Future

Recommended Improvements to the Interconnection Process



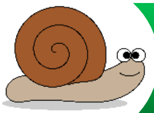
Even with FERC Order 2023, more guidance on Interconnection Studies is needed.

Possible IEEE 2800-2022 Adoption Methods



General Reference

- Full adoption of standard by general reference
- Specification of
  - technical minimum capability per IEEE 2800-2022
  - functional settings/ performance (in ranges of available settings)
- Decision whether to specify additional requirements or not
  - e.g., for non-exhaustive reqs.



Detailed Reference

- Full or partial adoption of std
- Clause-by-clause references
- Any additional requirements

Benefit: *Consistency to standard*

Risk: *Fragmentation of requirements, conformity assessment challenges, additional costs*

Full Specification

- All on the left
- Clause-by-clause own language
- Any additional requirements

Benefit: *No need to buy standard*

Risk: *Inconsistencies to standard and fragmentation of requirements, conformity assessment challenges, additional costs*

Inventory of Utility Approaches for IEEE 2800 Adoption

General Reference

- Florida Power and Light (FPL)
- Salt River Project (SRP)[2]
- Southwest Power Pool (SPP)[7]

Detailed Reference

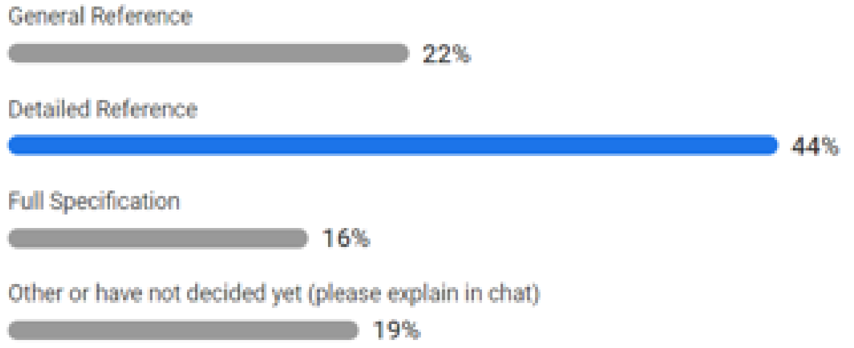
- Duke Energy[4]
- ISO New England[1]
- MISO[5]
- New York ISO[3]
- Southern Company[1]

Full Specification

- ERCOT[2]
- Ameren IL[6]

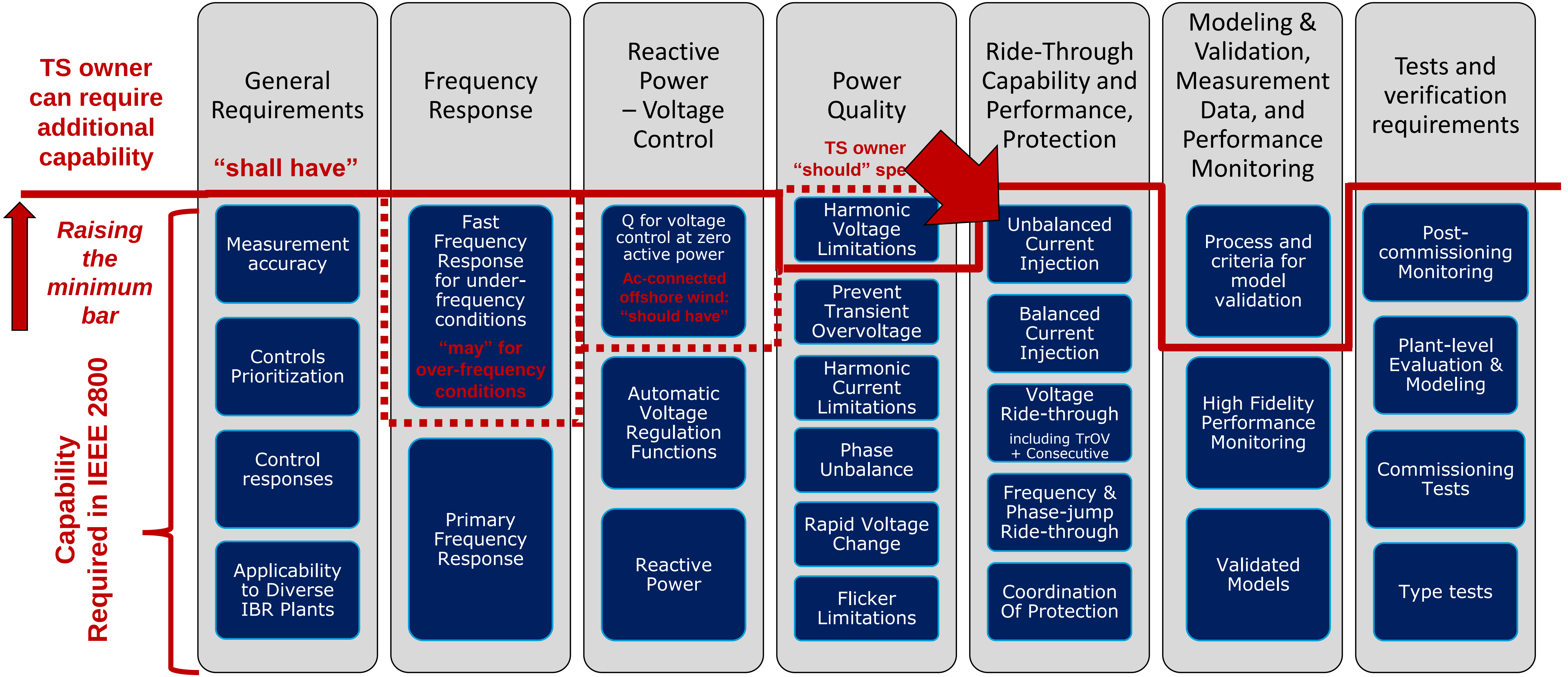
- Other utilities/ISOs considering IEEE 2800-2022 adoption: AESO, BPA, Great River Energy, Long Island Power Authority, Manitoba Hydro, TVA

Live Poll: Which adoption approach are you considering? 32
(based on February 15, 2023 webcast: link)



[1]: Presented on November 15, 2022 webcast: link
[2]: Presented on February 15, 2023 webcast: link
[3]: Presented on March 15, 2023 webcast: link
[4]: Presented on April 12, 2023 webcast: link
[5]: Presented on May 17, 2023 webcast: link
[6]: Presented on June 14, 2023 webcast: link
[7]: Presented on September 20, 2023 webcast: link

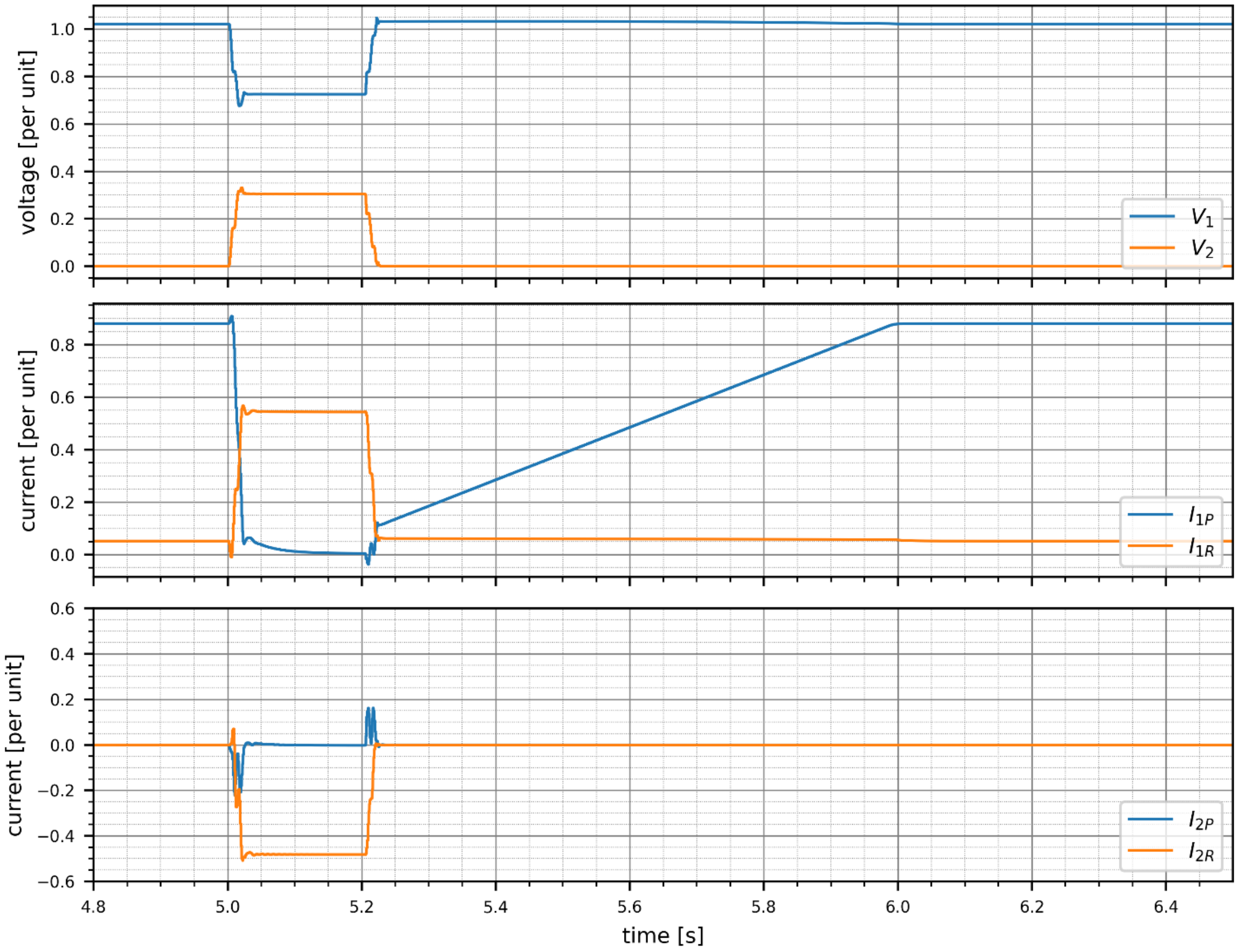
IEEE 2800-2022 Technical Minimum Capability Requirements



How to assess plant-level conformity for current injection during fault?

Example Use Case
IBR Performance Requirements

- Example IBR response for a LL fault
- EMT simulation domain allows for analysis of unbalanced conditions
- Helps the communication of performance requirements to the IBR developer



Ref: Southern Company Interconnection Requirements for Transmission Connected Inverter-Based Resources.
Online: http://www.oasis.oati.com/woa/docs/SOCO/SOCOdocs/SOCO_IBR_Interconnection-Technical-Requirements_Effective_08-06-2023.pdf

Remaining Gaps & Challenges

Related to Generic EMT Model Development

- Comprehensive validation and testing of EPRI's proposed model against IEEE 2800-2022 performance requirements is ongoing.
- Implementation and benchmarking of EPRI's proposed model in other EMT modeling software like EMTP-RV, PowerFactory, OpenDSS, etc. is ongoing.
- Continuous improvement and alignment with IEEE 2800-2022 and future revisions of the standard is necessary.

Related to Generic EMT Model Application

- IEEE 2800-2022 not yet broadly adopted by many ISOs/RTOs.
- Potential value of IEEE 2800-2022 not fully recognized by FERC.
- Revision of NERC Reliability Standards may consider IEEE 2800-2022 but will likely take many years.
- Neither EPRI's nor any other entity's proposed generic, IEEE 2800 conforming EMT model is "officially recognized".

Conformity assessment steps in IEEE P2800.2

Type Tests

Lab or field tests of individual IBR unit for model verification

IBR Unit Model Validation

Based on type test data

IBR Plant Model Development

Based on validated IBR unit model(s) and balance of plant

IBR Plant Design Evaluation

Simulations to assess plant conformity to IEEE 2800

Design Evaluation

As-built Installation Evaluation

Verification of installed plant

Plant construction complete

Commissioning Tests

Partial field assessment of plant performance

Post-commissioning Monitoring

Monitoring of plant performance during grid events

Post-Commissioning Model Validation

Based on commissioning test data

Periodic Tests and Verifications

This is a general diagram of the process.
Details are under development in IEEE P2800.2.
Some variations permitted.

More information at https://sagroups.ieee.org/2800-2/ and expression of interest to participate here.

The time to engage in IEEE P2800.2 is Now!

References

- Model Specification
  - Generic Photovoltaic Inverter Model in an Electromagnetic Transients Simulator for Transmission Connected Plants: PV-MOD Milestone 2.7.3. EPRI, Palo Alto, CA: 2022 Online: https://publicdownload.epri.com/PublicAttachmentDownload.svc/AttachmentId=82135
  - W. Baker, M. Patel, A. Haddadi, E. Farantatos, J. Boemer, "Inverter Current Limit Logic based on the IEEE 2800-2022 Unbalanced Fault Response Requirements", *2023 IEEE Power Engineering Society General Meeting*

- Model prototype in PSCAD™
  - *PRE-SW: Generic Photovoltaic Inverter Model in an Electromagnetic Transients Simulator for Transmission Connected Plants (PVMOD-EMT-IBR) v1.0 Beta.* EPRI, Palo Alto, CA: 2023. 3002025889 Online: https://www.epri.com/research/products/000000003002025889

- Model Validation
  - Draft Test Plan and Candidate Inverter List: Adaptive Protection and Validated MODels to Enable Deployment of High Penetrations of Solar PV (PV-MOD). EPRI, Palo Alto, CA: 2021. Milestones 1.3.2 and 1.3.3 report for DOE. Online: https://publicdownload.epri.com/PublicAttachmentDownload.svc/AttachmentId=74496
  - W. Baker, D. Ramasubramanian, A. Huque, J. Boemer, V. Gevorgian, P. Koralewicz, E. Mendiola, "Validation of the Fault Ride-Through Response of a Generic EMT Inverter Model by Laboratory Testing", *2023 IEEE Power Engineering Society General Meeting*

- FERC Order 2023: Improvements to Generator Interconnection Procedures and Agreements
  - FERC Transmission Reform Paves Way for Adding New Energy Resources to Grid. News Release. FERC. July 27, 2023. Online: https://www.ferc.gov/news-events/news/ferc-transmission-reform-paves-way-adding-new-energy-resources-grid

Content
(9:00 a.m. – 12:00 p.m.)

9:00 a.m. **Background and Motivation**
John Seuss & Jens Boemer

9:15 a.m. **High-level review of Power Electronics Basics for PV Inverters, IBR Controls, and Applicable IEEE Standards**
Jens Boemer

9:30 a.m. **Generic IBR Positive Sequence Models for Solar PV and Storage**
Deepak Ramasubramanian

10:20 a.m. **Break (time for some Q&A)**

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Jens Boemer

11:40 a.m. **High-level review of DER Modeling for Transmission Planning Studies**
Jens Boemer

11:45 a.m. **Additional Q&A / Overflow**

What Do We Mean By "Distributed Energy"?

Distributed Energy Resources (IEEE 1547)

- Resources connected at distribution level
  - May sometimes include resources connected at sub-transmission level
- Resources like
  - distributed generation
  - distributed storage
- Resources using technologies like
  - Inverters
  - Synchronous machines
  - May sometimes include other technologies

Other Resources (IEEE 2800, FERC O2222)

- Resources connected at bulk system level
  - May sometimes include resources connected at sub-transmission level
- Resources like
  - Large-scale generation ("dispersed energy res.")
  - Controllable loads
- Resources using technologies like
  - Inverters
  - Synchronous machines
  - May sometimes include other technologies

DER: "any generation or storage resource connected at distribution level"

EPRI's Collaborative Forum on FERC Order 2222

Findings

Interconnection

- Legacy DER may lack *capabilities* or not perform to support bulk system reliability
- Leading state PUCs not require DERs to have IEEE 1547-2018 capability / inverters to be certified under UL 1741 SB until Jan 1, 2023

Visibility & Configuration

- Lack of DER data collection and centralized databases
- Limited T&D coordination and data exchange
- Uncoordinated and unverified DER functional *settings*

Modeling & Analysis

- DERs often still modeled as net loads
- Aggregate DER (DER_A) model not commonly used


The New Aggregated Distributed Energy Resources (der_a) Model for Transmission Planning Studies: 2019 Update

EPRI (2019): [3002015320]

Operations & Control

- Lack of grid operator communication with DERs
- No ability to (re-)configure DER functional settings remotely
- Firm interconnection capacity

Standards

- NERC functional model and IEEE smart grids interoperability reference model
- DER Aggregator not a NERC registered entity
- Potential gaps in NERC reliability standards

EPRI's Collaborative Forum on FERC Order 2222

Recommendations

Interconnection Requirements

1

- Adoption of IEEE 1547-2018 with flexibility provided by 1547a-2020
- Require inverters to be certified under UL 1741 SB starting Jan 1, 2023

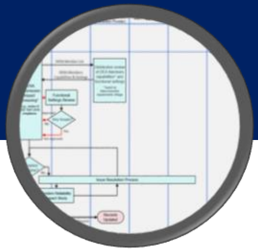
DER Data & Settings

- Collection and exchange of DER data across T&D interface

2

- Coordinate and verify DER functional *settings* that can impact bulk system reliability

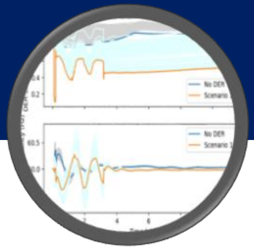
DERA Transmission Impact Screening



3

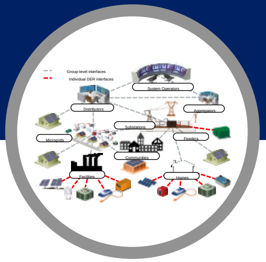
- Conduct Simplified Screening Tests during DERA Transmission Technical Review/ Registration
- Confirm DERA members' functional settings

Modeling & Simulation



- Utilize advanced DER and DERA models and appropriate parameterization
- As needed, use of Aggregate DER (DER_A) model or OEM-provided models, see also: https://www.epri.com/pvmod

DERA Integration into Grid Operations



- Further develop NERC and IEEE models and standards
- Consider registering DER Aggregators as a NERC entity

Transmission Planning Considerations for DER Wholesale Market Participation: An EPRI FO2222 Phase 1 Collaborative Report. EPRI. Palo Alto, CA: 2022. 3002020592 [Online] https://www.epri.com/research/products/000000003002020592

EPRI's Collaborative Forum on FERC Order 2222

Related Resources

Workstream Reports

3002020592

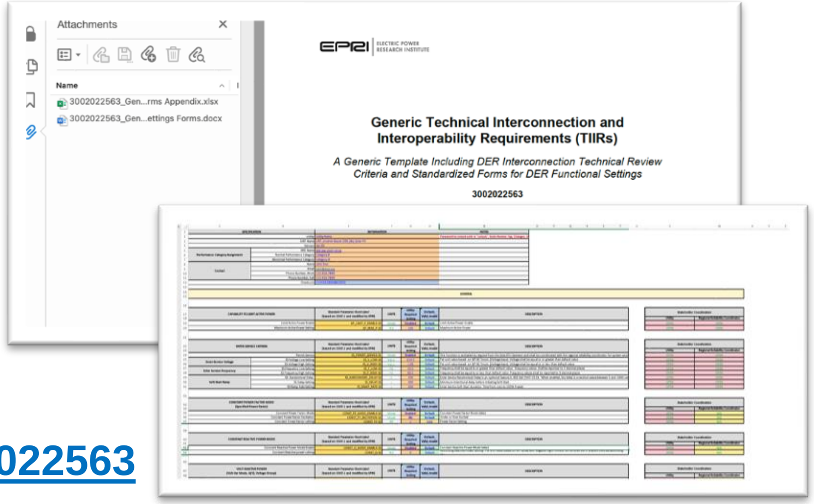
3002020591

NARUC Webinars

Link

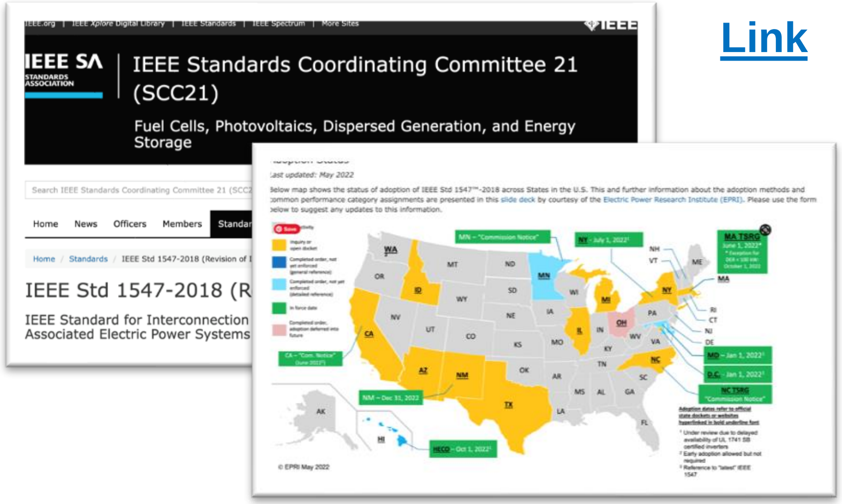
TIIR & Settings Templates

3002022563

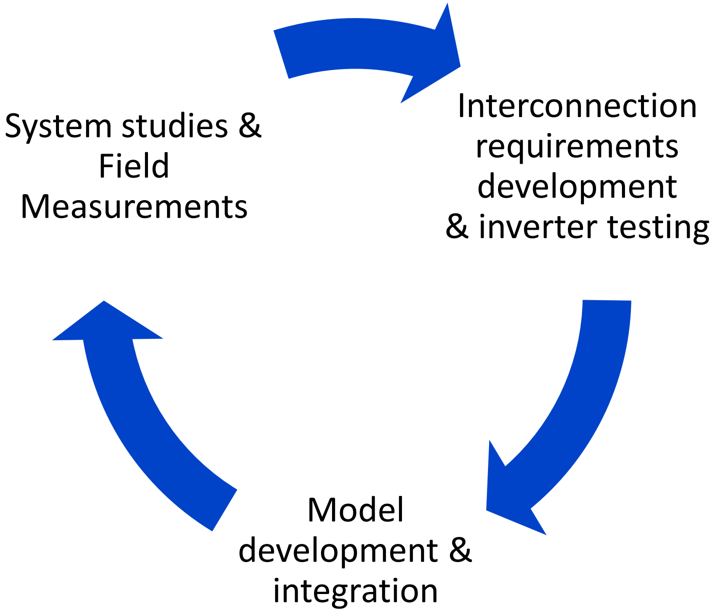


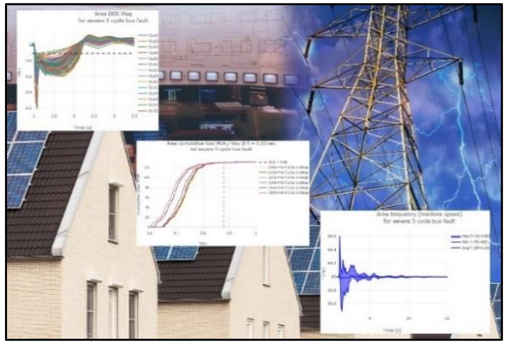
Websites & 1547 Adoption Maps

Link



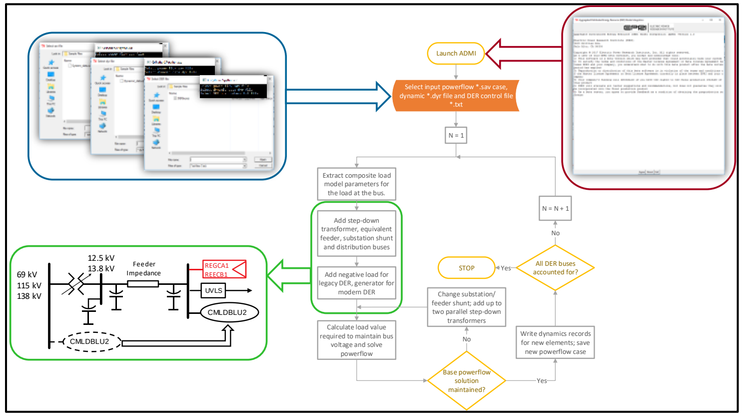
Research Related to Reliability Planning with DER





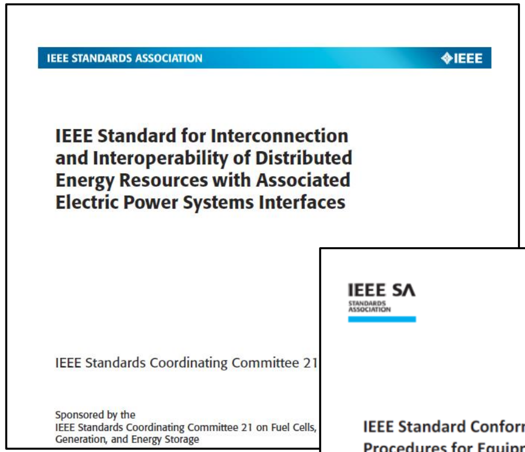
Case Studies Analyzing the Impact of Aggregated DER Behavior on Bulk System Performance (3002015415 & 3002019445)

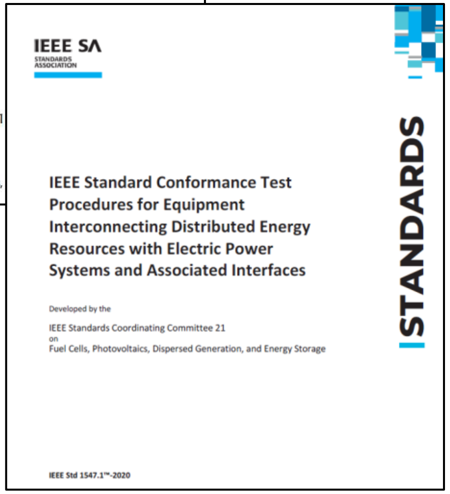
ADMI Tool (3002018213)

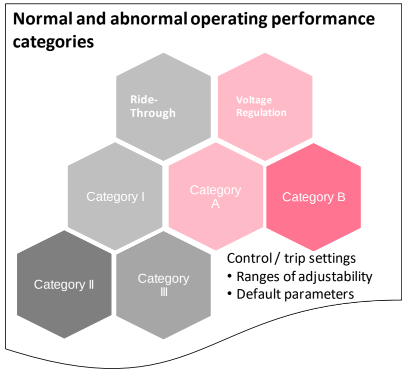


DER_A Model (3002015320)

PV-MOD Project (https://www.epri.com/pvmod)







Navigating DER Interconnection Standards and Practices (3002012048 & 3002022563)

Provide guidelines and tools to create a technical basis for assignment of DER abnormal performance categories and functional settings specified in IEEE Std 1547-2018 and that may impact bulk system reliability.

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Jens Boemer
Technical Executive
Grid Operations & Planning | DER Integration
(206) 471-1180
JBoemer@epri.com

Deepak Ramasubramanian
Senior Technical Leader
Grid Operations & Planning
(865) 617-7389
DRamasubramanian@epri.com

Mobolaji (“Mobs”) Bello
Technical Leader
Grid Operations & Planning
(865) 218-8005
MBello@epri.com

Thank You!

Q&A

- Ask clarifying questions,
- share practical challenges,
- go into further depth…

EPRI

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